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# Parabolic-trough solar collectors and their applications

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ABSTRACT

This paper presents an overview of the parabolic-trough collectors that have been built and marketed during the past century, as well as the prototypes currently under development. It also presents a survey of systems which could incorporate this type of concentrating solar system to supply thermal energy up to 400 °C, especially steam power cycles for electricity generation, including examples of each application.



**Contents**



*Abbreviations:* AC, Air-conditioning; AIST, National Institute of Advanced Industrial Science and Technology (Japan); APS, Arizona Public Service (United States); ARDISS, Advanced Receiver for Direct Solar Steam; ATS, Advanced Trough System; BMU, *Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit* (Germany); BOP, Balance of Plant; CC, Combined cycle; CFE, *Comisión Federal de Electricidad* (Mexico); CIEMAT, *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas* (Spain); COP, Coefficient of Performance; CPC, Compound parabolic concentrator; CSIRO, Commonwealth Scientific and Industrial Research Organization (Australia); CSP, Concentrated Solar Power; DCS, Distributed Collectors System; DE, Double-effect; DHW, Domestic hot water; DISS, Direct Solar Steam; DLR, *Deutsches Zentrum für Luft und Raumfahrt* (Germany); DNI, Direct Normal Irradiance; DSG, Direct Steam Generation; DOE, Department Of Energy (United States); DFVLR, *Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt* (Germany); EEA, Egyptian Electricity Authority (Egypt); EPC, Engineering procurement and Construction; FB, Flash boiler; FEMP, Federal Energy Management Program (United States); FPC, Flat plate collector; GEF, Global Environmental Facility; GUDE, *Grundlegende Untersuchungen zur Solares Direktverdampfung von Wasser nach dem Einspritzprinzip*; HCE, Heat Collector Element; HE, Heat exchanger; HTF, Heat transfer fluid; HRSG, Heat Recovery Steam Generator; IEA, International Energy Agency; INDITEP, Integration of Direct Steam Generation Technology for Electricity Production; IDAE, *Instituto para la Diversificación y el Ahorro Energético* (Spain); IIE, *Instituto de Investigaciones Eléctricas* (Mexico); IPDC, Iranian Power Development Company (Iran); IPH, Industrial process heat; IPP, Independent Power Project; ISCCS, Integrated Solar Combined-Cycle System; IST, Industrial Solar Technology Corporation (United States); KfW, *Kreditanstals fur Wiederaufbau* (Germany); LPC, Linear Parabolic Concentrating Collector; M.A.N., *Maschinenfabrik Augsburg-Nürnberg* (Germany); MED, Multi-effect Destilation; MOEE, Ministry of Electricity and Energy (Egypt); MSF, Multi-stage Flash; NEAL, New Energy Algeria (Algeria); NEP, New Energy Partners (Australia); NREA, New and Renewable Energy Authority (Egypt); O&M, Operation and maintenance; ONE, *Office National de l'Electricité* (Morocco); ORC, Organic Rankine Cycle; PF, Photo-Fenton; PG&E, Pacific Gas and Electric (United States); PSA, *Plataforma Solar de Almería* (Spain); PTC, Parabolic-trough collector; PURPA, Public Utility Regulatory Policies Act (United States); RMT, Roof Mount Parabolic Trough; RO, Reverse Osmosis; RPS, Renewable Portfolio Standard; RR, Rankine cycle with reheat; RREC, Rajasthan Renewable Energy Corporation (India); RfP, Request for Proposals; RRg, Rankine cycle with regeneration; RS, Rankine cycle with superheat; SACE, Solar Air Conditioning in Europe; SCE, Southern California Edison (United States); SE, Single-effect; SEGS, Solar Electric Generating Systems (United States); SERI, Solar Energy Research Institute (United States); SHAP, Solar Heat and Power (Italy); SHC, Solar Heating and Cooling; SIJ, *Solar Institut Jülich* (Germany); SO, Standard Offer; SPP1, Solar Power Plant One (United States); SSPS, Small Solar Power System Project; STEM, Solar Thermal Electricity for Mediterranean Countries; TC, Tubular Collector; TMR, *Tarifa Media de Referencia*; TOSCA, Trough with an Optimized SeCondary in Air; UAE, United Arab Emirates; UNAM, *Universidad Nacional Autónoma de México* (Mexico); UVAC, Universal Vacuum Collector; VC, V-Trough Collector; WGA, Western Governors' Association (United States).

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## 1. Introduction

Solar radiation is a high-temperature, high-exergy energy source at its origin, the Sun, where its irradiance is about 63 MW/m$^2$. However, Sun–Earth geometry dramatically decreases the solar energy flow down to around 1 kW/m$^2$ on the Earth's surface [1]. Nevertheless, under high solar flux, this disadvantage can be overcome by using concentrating solar systems which transform solar energy into another type of energy (usually thermal).

Solar radiation is converted into thermal energy in the focus of solar thermal concentrating systems. These systems are classified by their focus geometry as either point-focus concentrators (central receiver systems and parabolic dishes) or line-focus concentrators (parabolic-trough collectors (PTCs) and linear Fresnel collectors).

PTCs focus direct solar radiation onto a focal line on the collector axis. A receiver tube with a fluid flowing inside that absorbs concentrated solar energy from the tube walls and raises its enthalpy is installed in this focal line. The collector is provided with one-axis solar tracking to ensure that the solar beam falls parallel to its axis. PTCs can only use direct solar radiation, called beam radiation or Direct Normal Irradiance (DNI), i.e., the fraction of solar radiation which is not deviated by clouds, fumes or dust in the atmosphere and that reaches the Earth's surface as a parallel beam.

PTC applications can be divided into two main groups. The first and most important is Concentrated Solar Power (CSP) plants. There are currently several commercial collectors for such applications that have been successfully tested under real operating conditions. Typical aperture widths are about 6 m, total lengths are from 100 to 150 m and geometrical concentrating ratios are between 20 and 30. Temperatures are from 300 to 400 °C. CSP plants with PTCs are connected to steam power cycles both directly and indirectly. Although the most famous example of CSP plants is the SEGS plants in the United States, a number of projects are currently under development or construction worldwide.

The other group of applications requires temperatures between 100 and 250 °C. These applications are mainly industrial process heat (IPH), low-temperature heat demand with high consumption rates (domestic hot water, DHW, space heating and swimming-pool heating) and heat-driven refrigeration and cooling. Typical aperture widths are between 1 and 3 m, total lengths vary between 2 and 10 m and geometrical concentrating ratios are between 15 and 20. Most of the facilities are located in the United States, although some have recently been built in other countries. There are also some projects and facilities for other applications such as pumping irrigation water, desalination and detoxification.

## 2. Parabolic-trough collectors

This section presents a review of PTC models throughout the history of the technology, briefly mentioning their main features, applications, manufactures or public institutions involved in their development, and commercial availability.

### 2.1. The beginning

The first practical experience with PTCs goes back to 1870, when a successful engineer, John Ericsson, a Swedish immigrant to the United States, designed and built a 3.25-m$^2$-aperture collector which drove a small 373-W engine. Steam was produced directly inside the solar collector (today called Direct Steam Generation or DSG). From 1872 to 1875, he built seven similar systems, but with air as the working fluid [2]. In 1883, Ericsson constructed a large "sun motor" which was exhibited in New York. It consisted of a 3.35-m-long, 4.88-m-wide PTC, focusing solar radiation on a 15.88-cm-diameter boiler tube. The concentrator consisted of straight wooden staves, supported by parabolic curved iron ribs attached to the sides of the trough. The reflecting plates, made of flat window glass silvered on the underside, were fastened on these staves. The entire device tracked the sun manually. The engine's average speed during summer trials was 120 rpm and the absolute piston working pressure was 0.24 MPa [3]. In 1886, he experimented with a 1.86-kW solar engine [2]. Ericsson declined to give technical details about the boilers for protective reasons and, unfortunately, he died in 1889 before finishing a commercial version of his "sun motor", and his project was never continued.

The next reference is dated 1907, when Wilhelm Maier of Aalen (Germany) and Adolf Remshardt of Stuttgart (Germany), patented a PTC with DSG [4].

From 1906 to 1911, an American engineer, Frank Shuman, built and tested a number of solar engines. He used different types of non-concentrating and low-concentrating solar collectors (an absorber with flat reflector wings). Some of them were used for pumping irrigation water in Tacony, Pennsylvania (United States). In 1912, with the knowledge and experience gained in these preliminary tests, Shuman designed and installed a large irrigation pumping plant in Meadi, a small agricultural village south of El

Cairo, near the Nile River (Egypt). Shuman worked with Charles Vernon Boys, an English consultant, who suggested substantial changes in the construction of the collectors. Glass-covered boiler tubes were placed along the focal axis of a PTC. These solar collectors produced 0.1-MPa saturated steam directly inside the absorber tube. Each of the five north–south-facing PTC rows was 62.17 m long and 4.1 m wide, providing a total collecting surface of about 1250 $m^2$ and occupying nearly 4047 $m^2$ of land. The absorber tubes were 8.9 cm in diameter and had a concentration ratio of 4.6 which resulted in an overall peak absorber efficiency of 40.7% [2,5].

Shuman and Boys's reflector consisted of a number of strips of flat mirror, leaving narrow spaces between the adjacent edges so the wind could blow off dust on the mirrors through them. The absorber tubes and mirror system were supported on a lightweight crescent-shaped lattice, arranged at intervals and parallel to one another, and were tilted by means of a rack and pinion gear. To automatically align the absorber with the sun, a thermopile or thermostat was placed in the centre of the parabola (under the absorber tube). As long as it remained in the shadow of the tube, that is, the collector was correctly focused, the tracking motor did not turn. But as soon as the Sun's rays impinged upon the thermopile or the thermostat, either the thermopile generated a current or the thermostat a temperature increase, which activated the motor, turning the collector until the thermopile or thermostat was again shaded, and the motion stopped [6].

The Meadi plant was originally rated at 75 kW mechanical energy and, while reports on real output vary from just over 14 kW to a maximum of 54 kW by Pytlinski [2], it was suggested that with a good steam engine of the sort available at the time, the plant could have delivered some 41 kW [7]. This plant required an investment of $250,000 [5]. After the plant was started up successfully in 1913, Schuman was asked to build a number of other plants around the world, but in view of the outbreak of World War I and the low price of fuel in the international energy market, he aborted all his plans and the plant was abandoned in 1915 [7]. In spite of everything, the system was patented in 1917 [6].

In 1936, C.G. Abbot converted solar energy into mechanical power by using a PTC and a 0.37-kW steam engine. The author claimed an overall system efficiency of 15.5%. A single-tube flash-boiler encased in a double-walled evacuated glass sleeve to reduce heat loss was installed along the focal axis. The system was designed to raise full steam pressure within five minutes of exposure to the Sun's rays, producing saturated steam at 374 °C [2]. In 1938 he used a similar boiler in Florida to power a 0.15 kW steam engine. As quoted by Spencer, "Abbot suggested that a system using this boiler to produce steam at 225 °C should obtain a theoretical overall efficiency of 15.5% and a real efficiency of 11.7%" [7].

### 2.2. First commercial collectors

The interest in solar concentrating technology was negligible for almost 60 years. However, in reaction to the oil crisis of the seventies, international attention was drawn to alternative energy sources to supplement fossil fuels, and the development of a number of parabolic-trough systems was sponsored. Unfortunately, the range of products described in this section is no longer on the market.

The U.S. Government's Sandia National Laboratories and Honeywell International Inc. designed the first two collectors in the United States in the mid-70s. Both collectors were quite similar in concept and were prepared to work at temperatures below 250 °C. A third American company, Westinghouse, became involved in development of the incipient technology at its Production Technology Centre and adapted Sandia's design. In July 1975, three troughs were built and tested at Sandia. These 3.66-m-long collectors had a 2.13-m-wide aperture, and a 90° rim angle, and a 4-cm-diameter glass-encased black-chrome-coated carbon-steel absorber, with a 1-cm evacuated annulus. One of them employed an impregnated plywood shell, and another was made of fibreglass. Anodized aluminium by Alzak and back-silvered glass surfaces were attached to these support materials. A detailed cost study was done based on these designs [8].

In the 80s, this technology managed to enter the market, and some American companies, Acurex Solar Corp. (models Acurex 3001 and Acurex 3011), Suntec Systems Corp.–Excel Corp. (models IV and 360), Solar Kinetics Corp. (models T-700 and T-800), General Electric Co., Honeywell Inc. and Jacobs Del. Corp., manufactured and marketed a number of PTCs [9]. Table 1 shows the main characteristics of some of these collectors and also a PTC that was developed in the 90s by an Israeli company.

- Acurex Corp. 3001 and 3011 incorporated a Glaverbel thin-glass second-surface silvered reflector (0.8-mm-thick glass) and a black-chrome-coated steel absorber tube inside a non-evacuated borosilicate glass outer tube with anti-reflective coating. The

**Table 1**
Main characteristics of the first commercial PTCs.

| Company or institution | Acurex Corp. | | Solar Kinetics Inc. | | Suntec Systems Inc. | Solel Solar Systems |
|---|---|---|---|---|---|---|
| Model | 3001 | 3011 | T-700 | T-800 | IV | IND-300 |
| Country | USA | USA | USA | USA | USA | Israel |
| Max. operating temp. (°C) | 320 | 320 | 350 | 320 | 320 | 300 |
| Aperture area ($m^2$) | 72.29 | 78.09 | 77.96 | 85.95 | 108.52 | 7.8 |
| Aperture width (m) | 1.83 | 2.13 | 2.13 | 2.36 | 3.05 | 1.3 |
| Length (m) | 39.5 | 36.66 | 36.6 | 36.42 | 35.58 | 6.0 |
| Focal length (m) | 0.457 | 0.533 | 0.559 | 0.483 | 0.838 | 0.272 |
| Absorber tube diameter (mm) | 31.8 | 31.8 | 41.3[a](1), 31.8(2) | 41.3 | 38.1 | 0.022 |
| Cover tube diameter (mm) | 50.8 | 54.0 | 63.5(1), 52.1(2) | 60.0 | 76.0 | [b] |
| Reflector glass thickness (mm) | 0.8 | 0.8 | [b] | [b] | 4.8 | 4.0 |
| Rim angle (°) | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 | 100.0 |
| Acceptance angle (°) | 1.99 | 1.71 | 2.22(1), 1.71(2) | 1.97 | 1.43 | 1.962 |
| Geometric concentration ratio | 18.32 | 21.32 | 16.42(1), 21.32(2) | 18.19 | 25.48 | 18.64 |
| Peak optical efficiency | 0.708[c] | 0.827[c] | 0.736(1), 0.676(2) | 0.737 | 0.743 | 0.733 |
| Reflectance | 0.94 | 0.94 | 0.84 | 0.87 | 0.91 | [b] |
| Transmittance | 0.91 | 0.95 | 0.95 | 0.95 | 0.95 | 0.965 |
| Absorptance | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.96 |
| Emittance (at temp. (°C)) | 0.20 (300) | 0.20 (300) | 0.20 (300) | 0.20 (300) | 0.20 (300) | 0.07 (200) |
| References | [10–13] | [10,14] | [15] | [16] | [17] | [18,19] |

[a] Two different absorber tube outer diameters were tested: (1) 41.3 mm and (2) 31.8 mm.
[b] Unavailable datum.
[c] Authors remark no founded reasons for this large dissimilarity.



**Fig. 1.** Front (left) and rear (right) views of the Acurex 3001 collector.

support structure was a steel-tube backbone (20.3 cm diameter) with steel-sheet ribs [10–14].

The Acurex Corp. designed and marketed collectors with a shadow-band solar-tracking sensor with a multi-element shadow-detecting arrangement consisting of four photo-detectors, a central shadow-band perfectly aligned with the focal line and a high-transmittance glass window enclosure protecting the unit from the ambient [10,20]. Fig. 1 shows two pictures of the Acurex 3001 collector installed at the *Plataforma Solar de Almería* (PSA) (Spain), a research centre which belongs to the *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas* (CIEMAT).

- The Solar Kinetics T-700 and T-800 collectors were made of a 3M FEK-244 aluminized acrylic film and a black-chrome-coated absorber tube inside a non-evacuated borosilicate glass tube with anti-reflective coating. The T-700 collector was also tested with a tempered second-surface silvered reflector by Corning (0.94 reflectance), reaching a peak optical efficiency of 0.776 for the 41.3-mm diameter absorber tube and 0.732 for the 31.8-mm diameter absorber tube. The T-700 model support structure was aluminium monocoque and the T-800 was spot-welded steel-sheet monocoque [15,16].
- The Suntec Systems Inc. model IV collector consisted of a second-surface silvered glass mirror (4.8-mm-thick glass) backed with copper and Kraton. The receiver was a black-chrome-coated steel absorber pipe surrounded by a sealed glass outer tube containing argon gas at a partial vacuum. The support structure was a steel-tube backbone (20.3-cm diameter) and steel-sheet ribs [17].
- The IND-300 PTC, was manufactured by Solel Solar Systems (Israel). This collector was pioneer in incorporating a flat-glass cover with an anti-reflective coating. The reflector was aluminium and the absorber tube was stainless steel with a selective coating surrounded by a non-evacuated glass envelope with an anti-reflective coating. The flat cover also had an automatic cleaning system [18,19].

These PTCs were initially developed for IPH applications, however, the manufacturers found three barriers to successful marketing of their technology. First, a relatively strong marketing and engineering effort was required, even for small projects. Second, most potential industrial customers had cumbersome decision-making processes, which often resulted in a negative decision after considerable effort had already been expended. Third, the rate of return for IPH projects did not always meet industry criteria [21].

By that time, Europe had also begun to develop the PTC technology, although the effort was more modest than in the United States. The main company developing and marketing PTCs was *Maschinenfabrik Augsburg-Nümberg* (M.A.N.), in Munich (Germany). There were two M.A.N PTC models, the one-axis-tracking M-480, and the two-axis-tracking Helioman 3/32 (see Fig. 2). The main characteristics of these PTCs are given in Table 2.

The Helioman 3/32 is the only two-axis-tracking collector that has ever been marketed. The main advantage of two-axis-tracking collectors is their higher efficiency, because they always have a zero incidence angle. However, they also have several important disadvantages in their greater mechanical complexity (and, therefore, higher maintenance costs), less rigidity (entailing more failures and less operating time with high wind loads) and more auxiliary piping (involving higher solar field thermal losses).



**Fig. 2.** Helioman 3/32 collector.

**Table 2**
Main characteristics of the two M.A.N. PTCs.

| Company or institution | M.A.N. | |
|---|---|---|
| Model | Helioman 3/32 | M-480 |
| Max. operating temp. (°C) | 305 | 307 |
| Aperture area ($m^2$) | 32.4 | 91.2 |
| Aperture width (m) | 1.81 | 2.4 |
| Length (m) | 18 | 38 |
| Focal length (m) | 0.64 | [a] |
| Absorber tube diameter (mm) | 34.0 | 58.0 |
| Rim angle (°) | 70.5 | [a] |
| Geometrical concentration ratio | 16.85 | 13.17 |
| Peak optical efficiency | 0.71 | 0.77 |
| References | [11,13] | [22,23] |

[a] Unavailable datum.

**Table 3**
Main characteristics of the Luz PTCs [22,24–26].

| Model | LS-1 | LS-2 | | LS-3 |
|---|---|---|---|---|
| Year | 1984 | 1985 | 1988 | 1989 |
| Max. operating temp. (°C) | 307 | 349 | 390 | 390 |
| Aperture area ($m^2$) | 128 | 235.5 | 235.5 | 570.2 |
| Aperture width (m) | 2.55 | 5 | 5 | 5.76 |
| Length (m) | 50.2 | 47.1 | 47.1 | 99 |
| Focal length (m) | 0.68 | 1.40 | 1.40 | 1.71 |
| Mean focus distance (m) | 0.94 | 1.84 | 1.84 | 2.12 |
| Absorber tube diameter (mm) | 40.0 | 70.0 | 70.0 | 70.0 |
| Cover tube diameter (mm) | [a] | 0.115 | 0.115 | 0.115 |
| Rim angle (°) | 85 | 80 | 80 | 80 |
| Acceptance angle (°) | 1.918 | 1.59 | 1.59 | 1.37 |
| Geometric concentration ratio | 18.95 | 22.74 | 22.74 | 26.2 |
| Peak optical efficiency | 0.734 | 0.74 | 0.74 | 0.77 |
| Reflectance | 0.94 | 0.94 | 0.94 | 0.94 |
| Intercept factor | 0.87 | 0.89 | 0.89 | 0.93 |
| Transmittance | 0.94 | 0.95 | 0.95 | 0.96 |
| Absorptance | 0.94 | 0.94 | 0.94 | 0.96 |
| Emittance (at temp. (°C)) | 0.30 (300) | 0.24 (300) | 0.24 (300) | 0.15 (350) |

[a] Unavailable datum.

### *2.3. Collectors for CSP plants*

#### *2.3.1. Luz collectors*

The Israeli-American company Luz International Ltd., founded in 1979, designed three generations of PTCs, called LS-1, LS-2 and LS-3 (see Table 3 and Fig. 3), installed in Solar Electric Generating System (SEGS) plants (see Section 3.1.1).

The first two generations of collectors, LS-1 and LS-2, consisted of similar assemblies, mounted on a structure of similar length, but the aperture width of the LS-2 collector was twice that of the LS-1 collector. The structure is based on a rigid structural support tube, called the torque tube, which supports the steel profiles to which the parabolic mirrors are attached. In the LS-3, the torque tube is replaced by a metal lattice framework, the aperture width is 14% wider than the LS-2 and collector length is doubled. Changes were made in the pedestal and reflector supports, and the collectors are positioned by a hydraulic control system instead of the mechanical gear and cable system used in the LS-2. LS-3 collector design makes use not only of previous Luz power plant experience (SEGS-I to SEGS-VI), but also mass production, cost and performance requirements. However, SEGS plant operating experience shows that any benefit to cost has been clearly offset by associated performance and maintenance issues [21,24].

The Heat Collector Element (HCE) (absorber tube) used in Luz collectors (also manufactured by Luz) is a stainless-steel tube with a special selective coating, enclosed under vacuum by a glass tube or envelope. Conventional glass-to-metal seals and metal bellows achieve the vacuum-tight enclosure necessary to protect the selective coating against oxidation and reduce thermal losses, and accommodate for differences in thermal expansion between the steel tubing and the glass envelope. The outer tube is low-iron glass (max. 0.015%) and has an anti-reflective coating on both sides to maximize solar transmission. Hydrogen traps, often referred to as passive vacuum pumps, are installed in the vacuum cavity to absorb the hydrogen which migrates slowly across the steel tube [24]. Getters are also added to absorb gases which permeate into the evacuated space [26].

The selective coating used in the LS-1 and LS-2 collectors was black chrome, while a new ceramic-metal (cermet) layer 0.3-μm thick was applied by ionic bombardment under vacuum in the LS-3. The Luz concentrators are low-iron, back-silvered glass (4-mm thick) protected by five coatings (one copper, four varnish), manufactured by Flabeg Solar Int. (formerly Pilkington Solar Int., Germany). The glass is given its parabolic shape by heating it on accurate parabolic moulds in special ovens. Ceramic pads are cemented with a special adhesive to the back of the reflectors for mounting to the support structure [21,24,25].

In 1991 Luz filed for bankruptcy and in 1992, Solel Belgium (nowadays Solel Solar Systems Ltd.) purchased Luz manufacturing assets, providing a reserve for the Luz collector technology and key collector components [21]. Before the demise of Luz, the company had designed a forth generation collector, the LS-4, with the intention of studying DSG inside the absorber tubes. The LS-4 collector had a 10.5-m aperture width (almost double the LS-3),



**Fig. 3.** Front (left) and rear (right) views of LS-3 collector.

49 m total length and absorber outer diameter of 0.114 m. Working fluid temperature and pressure foreseen were 400 °C and 10 MPa, respectively. Two special features were that the absorber tube was tilted 8° and did not move, because at that time, no ball joints were able to work at such pressures. A previous prototype, the LS4-A2, had successfully been mounted and tested in the framework of the Advanced Trough System (ATS) Project in the Luz test facilities in Jerusalem (Israel). This prototype was similar in size to the LS-3, but the absorber tube was carbon steel instead of stainless steal, and the inner absorber diameter was 0.059 m instead of 0.066 m. Unfortunately, the company disappeared before finishing this project and the LS-4 collector never reached the market [24,26–28].

### 2.3.2. EuroTrough collector

In 1998, a consortium of European companies and research laboratories (Abengoa/Inabensa, Fichtner Solar, Flabeg Solar Int., *Schlaich Bergermann und Partner*, Iberdrola, Solel Solar Systems, CIEMAT, CRES and DLR) was created to develop a new generation of PTCs for cost-efficient CSP plants, since the current LS-3 design was no longer competitive [21,29].

The EuroTrough collector was the result of analysis of several different collector structures (see Fig. 4) with geometric characteristics similar to the LS-3 collector, but with the main difference in the rectangular torque-box support structure, which combines the LS-2 torque tube design benefits of torsional stiffness and alignment with the reduced cost of an LS-3-like truss design. The first version, the ET-100, was developed under the European Commission EuroTrough I Project (4th Framework Program contract number JOR3-CT98-00231). Each 100-m collector was made up of 8 modules and had an aperture area of about 545 $m^2$. As the torque-box's high torsional stiffness allowed the original length of the collector assembly to be extended, in the second version, the ET-150, developed under European Commission Project EuroTrough II (5th Framework Program contract number ERK6-CT-1999-00018), the number of modules per collector was increased to 12, collector length to around 150 m and aperture to about 820 $m^2$. Both versions were fully qualified in 2000–2002 at the PSA using half a collector with a synthetic heat transfer fluid (HTF) at around 400 °C operating temperature [21,29,30]. The EuroTrough collector has the following advantages over previous PTC designs [21,29]:

- Less collector structure deformation under gravity and wind loads, thereby reducing torsion and bending of the structure during operation, leading to increased optical performance.
- The extended collector length from 100 m (ET-100) to 150 m (ET-150), made it possible to reduce the number of collector field drives required, as well as the number of interconnecting pipes, lowering thermal losses and the total cost.
- Less shading due to the improved absorber support design.
- The steel structure weight is about a 14% lighter than the LS-3 collector.
- Transportation requirements optimized for best packing.
- Fewer components, increasing large-scale production capacity.
- Lower operation and maintenance requirements.
- Simplified manufacturing, reducing on-site assembly costs.
- All of the above result in about a 10% cost reduction.

The EuroTrough uses the same mirrors as the LS-3 (manufactured by Flabeg). The current commercial deployment of this technology has awakened the interest of some traditional glass companies in this type of mirror. Two of them, Saint-Gobain Solar [31] and Rioglass Solar [32,33], already market one.

The Solel Universal Vacuum Collector (UVAC) by Solel, which improved the original Luz absorber tube, but did not change the size, was successfully tested in the EuroTrough collector [21]. By that time, Schott Solar (Germany) had developed a similar absorber tube, which differed mainly in the expansion bellow and metal-glass seal [34,35]. Both companies have been working on them since then, achieving a lower-emittance (around 0.14 at 400 °C) and more stable, durable absorber-tube selective coating. The current versions are the Solel UVAC2008 [36,37] and the SCHOTT PTR 70 [38,39].

The third-generation EuroTrough collector, called the SKAL-ET, was developed under a project funded by the German government (*Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit*, BMU), and has already been validated and commissioned in a commercial plant. This version also has 12 slightly modified modules. Seven collectors with an overall aperture area of 4360 $m^2$ were erected at the commercial SEGS-V plant (California, USA), and have been operating as an integral part of the solar field, contributing around 0.7 $MW_e$ to the electricity production since April 2003. In September 2003, special test instrumentation was installed in the loop to measure its performance and monitor operation. In addition, a new collector solar-tracking sensor and control system were developed and tested in over 8000 h of operation, demonstrating its high precision [40,41].

Some minor modifications aimed at solar field cost reduction were made in the previous versions of the EuroTrough. One of the main modifications was the substitution of rectangular hollow profiles by hot-rolled profiles. The lower specific material cost for these profiles compensates the increased collector structure weight. This new Model AS1 was selected for the Andasol-1 and 2 CSP plants (Granada, Spain) [42].

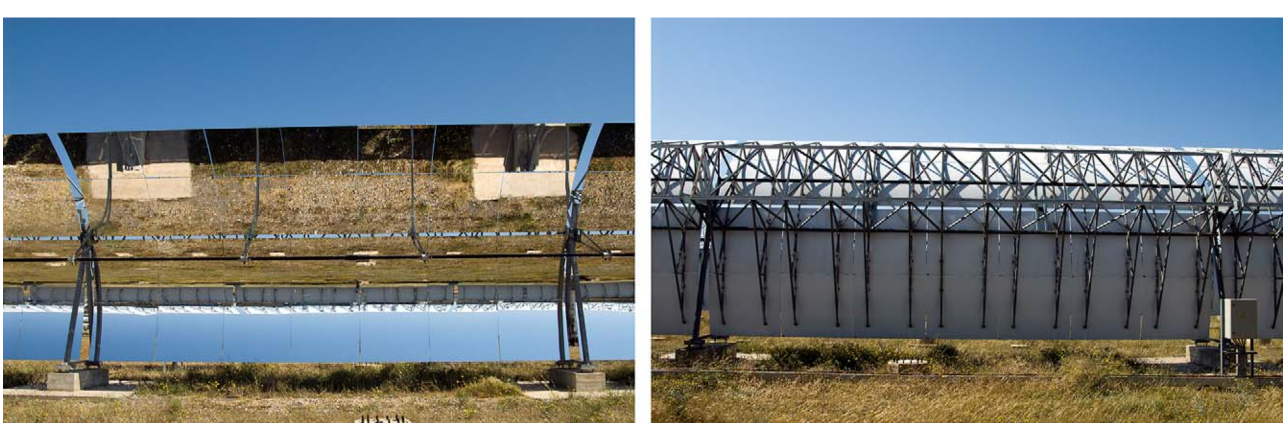


**Fig. 4.** Front (left) and rear (right) views of EuroTrough collector.

#### 2.3.3. Other current collectors

Other electricity production designs following the EuroTrough philosophy have recently appeared. The main idea is to maintain certain geometric parameters using key components available on the market, whilst increasing the benefits and reducing costs. This is the philosophy behind the following collectors:

- The American company Solargenix Energy (Duke Solar until April 2003), with funding from the Department of Energy (DOE), has developed two generations of PTCs (SGX1 and SGX2) in an attempt to improve efficiency and lower cost. The SGX1 collector is patterned after the LS-2 collector, except it is twice as long. Therefore, the components (mirrors and receivers) are the same. The main effort was invested in the lightweight space frame structure, which is made entirely of aluminium and is superior in terms of shipping, handling during manufacturing, field installation and corrosion resistance. In addition, this collector also incorporates newly developed and improved subsystems, e.g., solar-tracking controls, support pylons and drive units. It increases performance by 10% and decreases cost by over 20% compared to previous-generation troughs. The main advantage in the second generation, SGX2, is the reduced manufacturing time. In 2006, 55% of Solargenix Energy was bought by the Spanish company, Acciona Solar Power [21,43–45].
- The Spanish company, SENER, developed the SENERTROUGH-I collector (see Fig. 5), which is the same size as the LS-3. However, the support structure returns to the LS-2 torque-tube concept. This high-torsional-stiffness cylindrical tube is made of steel sheet, and varies in thickness and quality depending on wind load requirements. Cantilever arms, made using metal-sheet stamping techniques, connect the mirrors to the central torque tube, thus reducing both manufacturing and erecting costs and total mass (about 30%). Two prototype modules were evaluated at the PSA in 2005 [46] and a complete 600-m loop was installed in the Andasol-1 CSP plant (Granada, Spain) for its validation [47]. This collector was also selected for the Extresol-1 CSP plant (Extremadura, Spain) [47]. The next generation, SENERTROUGH-2, being designed in collaboration with key component suppliers (Flabeg Solar International and SCHOTT), has a wider aperture and absorber tube diameter [48].
- Albiasa Solar (Spain) has also developed and tested a new collector, called the Albiasa Trough. Again, the size is the same as the LS-3, but the design concept is similar to the LS-2. The main difference from the Sener design is the torque tube. In this case, the cylindrical tube is made of four 90°-arc pieces (made of cold-rolled galvanized-steel profiles) with half-T flaps assembled with screws. The arms are hot-formed galvanized steel. This special torque tube concept provides a very robust closed section with improved torsional and flexural stiffness, and lowers manufacturing time and costs [49,50].
- The Italian National Environmental & Renewable Research Centre (ENEA) is developing a new PTC the same size as the LS-3 collector. The concentrator is a honeycomb sandwich with larger-than-conventional facets (half a parabola), and is intended for a maximum operating temperature of 550 °C. The HTF will be molten salt [45,51].



**Fig. 5.** Rear view of SENERTROUGH collector.

Other collectors of different sizes and with different geometric concepts have recently appeared on the market or are currently under development:

- Solel Solar Systems is also working on an advanced design, the Solel-6, based on the LS-3 dimensions, but with the torque tube structural approach. A test loop is being erected at Sde Boker (Israel) [37,45].
- A new DSG collector developed by the German company, Solarlite, for steam temperatures up to 400 °C has already been used in two pilot plants. The modules are made out of lightweight glass-fibre reinforced plastic with high-reflectance aluminium (88%). Each one is 1.0 m long and has an aperture width of 2.33 m [52].
- The Trough with an Optimized SeCondary in Air (TOSCA) collector, manufactured by the Chinese company, Huiyin Group, implements a new geometric concept. It employs the non-evacuated secondary-reflector Solarmundo receiver, developed for Fresnel collectors. This secondary reflector requires less concentrator optical precision, and therefore, the concentrator is not a parabolic-trough but a lower-cost circular one [53].
- Industrial Solar Technology (IST), an American company recently acquired by a Spanish company, Abengoa Solar, and now called IST Solucar, is developing the PT-2 collector, which is a scale-up of its PT-1 (see Section 2.4.1). The PT-1 has a non-evacuated receiver and a metal sheet reflector, and has been marketed in the United States since 1984 for supplying hot water. The PT-2 incorporates an evacuated tube, but, like the PT-1, it is made of a flexible sheet reflector (polished or silvered aluminium), in a lightweight integrated structural reflector with little material (which involves a lower cost) and a versatile geometry. The total and focal lengths are similar to the LS-3, but aperture width is 4.4 m and rim angle is 72° [45,54,55].
- SkyTrough is a new collector manufactured by SkyFuel (USA) with dimensions similar to the LS-3 (1.71 m focal length, 6 m aperture width, 112 m total length and 82.5° aperture angle), which differs mainly in the reflector, a silver-metallised polymer film called ReflecTech, which is inexpensive, accurate (94% reflectance), weather resistant, easy-to-maintain, unbreakable, lightweight and commercially proven. The ReflecTech film is laminated onto curved aluminium panels which are assembled on site on an aluminium space frame with low manpower requirements (no welding necessary). It also incorporates a new version of the Schott receiver and the SkyTracker solar-tracking control [56].
- Soponova 4.0 is a small low-cost, low-land-use collector for low-temperature power generation (up to 300 °C), manufactured by Sopogy MicroCSP (USA) and specially designed for scalable distributed solar solutions (from 250 kW to 20 MW). It uses a non-vacuum receiver and a metal-sheet reflector, with a 1.52-m aperture width and 3.66-m total length [57].

### 2.4. Collectors for applications at temperatures up to 250 °C

IPH production is a major PTC target application in which a solar field can be successfully integrated for supplying thermal energy at temperatures up to 250 °C. Nevertheless, there are other applications, such as heat-driven refrigeration and cooling,

**Table 4**
Main characteristics of the small and medium-sized commercial PTCs.

| Company or institution | IST | | Solitem | NEP Solar and CSIRO[a] |
|---|---|---|---|---|
| Model | PT1 (ground) | RMT (roof) | PTC 1800 | Polytrough 1200 |
| Country | United States | United States | Turkey and Germany | Australia |
| Max. operating temp. (°C) | 288 | 205 | 220 | 220 |
| Working fluid | Press. water | Press. water | [a] | Press. water |
| Aperture area ($m^2$) | 14.03 | 4.22 | 9.162 | 28.8 |
| Aperture width (m) | 2.3 | 1.148 | 1.8 | 1.2 |
| Length (m) | 6.1 | 3.677 | 5.09 | 24.0 |
| Focal length (m) | 0.80 | [a] | 0.78 | 0.65 |
| Absorber tube diameter (mm) | 51.0 | 25.4 | 38.0 | 25.4 |
| Cover tube diameter (mm) | 75.0 | 51.0 | 65.0 | [a] |
| Rim angle (°) | 72.0 | [a] | 60.0 | 50.0 |
| Acceptance angle (°) | 2.41 | [a] | 2.09 | 1.85 |
| Geometric concentration ratio | 14.36 | 14.39 | 15.08 | 15.04 |
| Peak optical efficiency | 0.7625 | 0.7625 | [a] | [a] |
| Reflectance | 0.89 | 0.89 | 0.89 | [a] |
| Transmittance | 0.95–0.96 | 0.95–0.96 | 0.95 | [a] |
| Absorptance | 0.96–0.98 | 0.96–0.98 | [a] | [a] |
| Emittance (at temp. (°C)) | 0.15–0.25 (80) | 0.15–0.25 (80) | [a] | [a] |
| References | [58,59] | | [60–62] | [61,63,64] |

[a] Commonwealth Scientific and Industrial Research Organization.

low-temperature heat demand with high consumption rates, irrigation water pumping, desalination and detoxification. On the one hand, these temperature requirements cannot be efficiently reached by conventional low-temperature collectors (flat plate collectors (FPC), compound parabolic concentrators (CPC) or evacuated tubes). On the other hand, use of solar concentrating systems with high concentration ratios and high-temperatures absorbers would be unnecessarily expensive.

These applications have stronger solar field space constraints than CSP plants. Factories today are usually located in industrial zones or estates where the price of land is expensive, so installing the solar field on rooftops should be a real possibility. Therefore, these PTCs should be modular, small (aperture width under 3 m), lightweight and, of course, low-cost.

### 2.4.1. Commercial collectors

Table 4 summarises the main characteristics of commercial PTCs specially designed for supplying thermal energy to such applications. Some additional information about these collectors and their manufacturer is given below:

- The IST Corp., founded in the United States in 1985 and recently acquired by the Spanish company, Abengoa Solar, markets two PTCs, the Parabolic Trough model (PT1) for ground mounting and the Roof Mount Parabolic Trough model (RMT). The reflector is acrylic aluminium or enhanced-polished aluminium (although a silvered mirror was also tested). The absorber is a black nickel-coated (optionally black-chrome-coated) steel absorber pipe surrounded by a non-evacuated glass enveloped with sol–gel anti-reflective coating. It has an aluminium rib support structure [58,59].
- The Solitem Company (Turkey, Germany) markets the PTC-1800 which the DLR helped design and evaluate. It consists of a 0.5-mm aluminium reflector (Mirosun by Alanod), a stainless-steel absorber tube (1.25-mm-thick wall) that has been galvanically coated with a selective surface, and a non-evacuated glass envelope with anti-reflexive coating (2.2-mm-thick wall). The support structure is made of aluminium ribs and 0.8-mm aluminium sheet. A back torque tube provides additional stiffness [60–62].
- The Australian company, New Energy Partners Pty Ltd. (NEP), has developed the NEP SOLAR Polytrough 1200 in collaboration with Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), and has recently begun to market it. This collector consists of composite mirror carrier panels and a steel torque tube. The mirror carrier panels are made of polymeric composite materials and the mirror surface is aluminium sheet with a polymer coating made by physical vapour deposition. The absorber tube is a fixed non-evacuated glass-encased stainless-steel pipe with a selective coating [61,63,64].

Finally, a new collector that must be added is the Linear Parabolic Concentrating Collector (LPC) manufactured by the Italian company, Solar Heat and Power (SHAP). This PTC has a flat-glass cover, aperture width of 1.3 m and total length of 6 m. The maximum operating temperature is between 200 and 250 °C [65].

### 2.4.2. Prototypes

As a consequence of the growing interest in this technology, several public institutions and private companies have recently developed a number of prototypes. A brief description of these prototypes is presented below, and the main features are summarized in Table 5:

- The PTC-1000 prototype was developed by the German research institutions, *Solar Institut Jülich* (SIJ) and DLR, in collaboration with *Solitem GmbH* (Germany and Turkey) and *Alanod* (Germany) from 2003 to 2005. The rotation axis and absorber tube are on the same

**Table 5**
Main characteristics of some small and medium-sized PTC prototypes.

| Company or institution | SIJ, DLR; Solitem and Alanod | AEE INTEC, Knopf Design, Button Energy and Solution | IIE |
|---|---|---|---|
| Model | PTC 1000 | Parasol | IIE |
| Country | Germany | Austria | Mexico |
| Max. operating temp. (°C) | 200 | 200 | 400 |
| Working fluid | Press. water | Press. water | [a] |
| Aperture area ($m^2$) | 2.0 | 2.0 | 15.46 |
| Aperture width (m) | 1.0 | 0.5 | 2.3 |
| Length (m) | 2.0 | 4 | 6.72 |
| Focal length (m) | 0.205 | 0.1 | 0.78 |
| Absorber tube diameter (mm) | [a] | 12.0 | 27.0 |
| Rim angle (°) | 99.0 | 103.0 | 72.0 |
| Acceptance angle (°) | [a] | 1.34 | [a] |
| Geometric concentration ratio | [a] | 13.26 | 27.12 |
| Peak Optical Efficiency | 0.70 | 0.55 | [a] |
| References | [61,66–68] | [61] | [69] |

[a] Unavailable datum.

axis and, therefore, the absorber is in a fixed position during operation, avoiding flexible pipe connections. The reflector is a silver-coated aluminium sheet (Mirosilver by Alanod), the support structure is stainless steel, and the absorber tube is the Vacuum Standard Sydney tube by Linuo-Paradigma [66]. This collector has an anti-reflective glass cover by Flabeg Solar International. Both ends are reflecting surfaces to avoid collector end losses [61,67]. In March 2007, the SIJ started another research project with four German industrial partners to improve its technical characteristics and thermodynamic performance [68].

- The Parasol prototype, under development at the Austrian Institute for Sustainable Technologies (AEE INTEC), in collaboration with the Austrian companies *Knopf Design*, *Button Energy Energiesystem GmbH* and *Solution Solartechnik GmbH*, has a parabolic glass concentrator with an inner aluminium mirror by Alanod. The trough is covered by a flat glass that prevents dirt from entering and ensures stability. The stationary absorber tube is at the collector centre of gravity. The absorber is a non-evacuated, glass-covered, stainless-steel tube with a selective coating. After the first tests, a second prototype was manufactured, with improved low-iron safety glass instead of standard window glass, Poligrat absorber coating instead of solar varnish, more precise positioning of the absorber tube, and 12 mm absorber diameter instead of 8 mm [61].
- The *Instituto de Investigaciones Eléctricas* (IIE), Mexico, started to develop a PTC prototype for IPH in 2001. The support structure is tubular steel, the reflective surface is 0.5-mm anodized-aluminum sheet, and the absorber is a steel-tube painted black and surrounded by a non-evacuated Pyrex glass tube. A second improved prototype was developed, with a lighter support structure. The solar-tracking unit was moved from the end of the collector to the middle in order to balance the torsion, and the receiver supports were changed from a combination of viton and neoprene to Teflon. This second prototype was installed in an industrial laundry in the north of Mexico in 2003. At the end of 2004, an automobile company requested the IIE to construct and install 2 PTCs (with Pyromark selective coating) for sanitary water heating [69].

## 3. Applications

### *3.1. CSP plants*

Both world total final energy consumption and world $CO_2$ emissions have doubled in the last 35 years [70]. The limited supply of fossil hydrocarbon resources and the negative impact of $CO_2$ emissions on the global environment dictate increased usage of renewable energy resources. CSP is the most likely candidate for providing the majority of this renewable energy, because it is amongst the most cost-effective renewable electricity technologies and can make a substantial contribution towards international commitments to reduce the increase in the level of greenhouse gases and their contribution to climate change [71,72]. Furthermore, many countries are exploring various sources of renewable energy to reduce their dependence on foreign imports to meet their energy requirements. As solar energy is the most abundant and geographically widespread resource, it offers advantages over other energy resources [73].

To emphasize the magnitude of the solar resource, an illustrative calculation is useful. Even under the assumption that only 1% of the land area in the world with enough solar radiation were used for CSP plants, the potential annual electricity generation would still be higher than total world electricity production in the year 2000 [26], and regarding environmental benefits, each square meter of solar field is enough to avoid the annual emissions of 200–300 kg of $CO_2$ [71].

Appropriate site locations for CSP plants are normally in arid to semi-arid regions, where the DNI resource is very high, because acceptable production costs of commercial CSP plants are typically where DNI exceeds about 1700 kWh/m$^2$year [26] or 2000 kWh/m$^2$ year [71]. Typical site regions with these conditions are located in the "solar belt" within 40° latitude north and south. Therefore, the most promising areas in the world include the North African Desert, the Arabian Peninsula, major portions of India, central and western Australia, the high plateaus of the Andean states, north-eastern Brazil, northern Mexico and, of course, the United States Southwest. Promising site locations in Europe are found in southern Spain and several Mediterranean islands [26]. All commercial CSP plants are north–south oriented, because this maximizes the amount of power produced along the year. The higher the latitude, the more necessary this becomes.

There are two ways to integrate a PTC solar field in a steam-turbine power plant, directly, that is, generating steam in the solar field (DSG technology), or indirectly, by heating thermal oil in the solar field and using it to generate steam in a heat exchanger (HTF technology). In both cases, solar fields can drive all types of steam-turbine power plant cycles, Rankine with Superheat (RS), Rankine with Reheat (RR) and Rankine with Regeneration (RRg). Another option is an Organic Rankine Cycle (ORC), which generates vapour from an organic fluid instead of steam in a lower-temperature cycle. Hybridising with fossil fuels can be done in several ways, using an auxiliary system for heating the HTF during low and non-solar hours, or introducing the fossil back-up in the steam cycle, in the evaporation, superheat or reheat zones.

Another interesting option is incorporation of a solar system in a combined cycle (CC), called Integrated Solar Combined-Cycle System (ISCCS), in which two different thermodynamic cycles, a steam-turbine Rankine cycle and gas-turbine Brayton cycle, are combined in a single system through a Heat Recovery Steam Generator (HRSG). Fuel is combusted in the gas turbine in the conventional way, and the hot exhaust gas goes through the HRSG. Here the energy from the gas generates and superheats steam to be used in the steam-turbine bottoming cycle. Solar energy from a PTC solar field can be integrated either at high pressure in the HRSG or at lower pressure directly in the low pressure casing of the steam turbine [26]. The general concept is an oversized steam turbine, using solar heat for steam generation and gas turbine waste heat for preheating and superheating steam [74].

Since the solar steam is only feeding the CC steam turbine, which is a third of its total power, the solar share is about 10% [75]. Some studies show that the ISCCS configuration could reduce the cost of solar power by as much as 22% over the blended (25% fossil) cost of power from a conventional CSP plant of similar size [76]. In addition, an ISCCS offers three other advantages. The solar energy to electricity conversion is more efficient, the incremental costs for a larger steam turbine are less than the overall unit cost in a solar-only plant, and an integrated plant does not have the thermal inefficiencies associated with the daily steam turbine start-up and shut-down [77].

#### *3.1.1. SEGS plants*

The first oil crisis in the early 70s marked the beginning of modern development of CSP plants worldwide. R&D activities were started on several continents, and experimental and pilot solar power plants were erected and operated. But it was in the United States where parabolic-trough solar technology reached its maximum maturity, in nine commercial SEGS plants built in the Mojave Desert in California (where the average DNI is up to 2727 kWh/m$^2$ year). These plants, developed by Luz International Ltd., range in size from 14 to 80 $MW_e$ and represent 354 $MW_e$ installed capacity. Current PTC technology is the most proven and lowest-cost large-scale solar power technology, primarily because of these plants [21].

**Table 6**
Main characteristic of the SEGS plants [23,24,26,79].

| SEGS | I | II | III | IV | V | VI | VII | VIII | IX |
|---|---|---|---|---|---|---|---|---|---|
| Location | Dg[a] | Dg | KJ[b] | KJ | KJ | KJ | KJ | HL[c] | HL |
| First year of operation | 1984 | 1985 | 1986 | 1986 | 1987 | 1988 | 1988 | 1989 | 1990 |
| Net output capacity ($MW_e$) | 13.8 | 30 | 30 | 30 | 30 | 30 | 30 | 80 | 80 |
| Net electricity production (GWh/year) | 30.1 | 80.5 | 91.3 | 91.3 | 99.2 | 90.9 | 92.6 | 252.8 | 256.1 |
| Land area (ha) | 29 | 67 | 80 | 80 | 87 | 66 | 68 | 162 | 169 |
| Solar field aperture area (ha) | 8.3 | 19.0 | 23.0 | 23.0 | 25.1 | 18.8 | 19.4 | 46.4 | 48.4 |
| Collectors[d] | LS1/LS2 | LS1/LS2 | LS2 | LS2 | LS2 | LS2 | LS-2/LS3 | LS3 | LS3 |
| Solar field outlet temperature (°C) | 307 | 321 | 349 | 349 | 349 | 391 | 391 | 391 | 391 |
| Annual solar field thermal efficiency (%) | 35 | 43 | 43 | 43 | 43 | 43 | 43 | 53 | 50 |
| Heat transfer fluid | ESSO 500 | VP1 | VP1 | VP1 | VP1 | VP1 | VP1 | VP1 | VP1 |
| Gross turbine output ($MW_e$) | 14.7 | 33 | 33 | 33 | 33 | 33 | 33 | 89 | 89 |
| Power fluid | steam | steam | steam | steam | steam | steam | steam | steam | steam |
| Power fluid pressure (MPa) | 3.53 | 2.72 | 4.35 | 4.35 | 4.35 | 10 | 10 | 10 | 10 |
| Power fluid temp. (°C) | 415[e] | 360 | 327 | 327 | 327 | 371 | 371 | 371 | 371 |
| Power cycle | RS/RRg | RS/RRg | RS/RRg | RS/RRg | RS/RRg | RS/RRg/RR | RS/RRg/RR | RS/RRg/RR | RS/RRg/RR |
| Global average annual efficiency (%) | 9.7 | 12.4 | 10.7 | 10.7 | 10.2 | 12.3 | 13.4 | 13.9 | 13.9 |
| Useful lifetime (year) | 20 | 25 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |

[a] Daggett.
[b] Kramer Junction.
[c] Harper Lake.
[d] See Table 3 and Fig. 3.
[e] Steam generated by solar energy, superheated by natural gas (18% of energy input).

The Luz Group, founded by Arnold Goldman in Israel in 1979, consisted of Luz International Ltd., based in Los Angeles (United States), and 7 subsidiaries. Before installing the first solar power plant, the company had spent several years developing components and systems at a test facility in Jerusalem, and was responsible for the construction and operation of two process heat facilities (a farm produce industry and a textile factory) in Israel [24,26].

In 1983, Southern California Edison (SCE) signed an agreement with the Acurex Corp. to purchase power from a solar electric PTC power plant. Acurex was unable to raise financing for the project. Consequently, Luz negotiated a 30-year power purchase agreements with SCE for the SEGS-I and SEGS-II plants. Later, with the advent of the California Standard Offer (SO) power purchase contracts for qualifying facilities under the Public Utility Regulatory Policies Act (PURPA), Luz was able to sign a number of individual SO contracts with SCE that led to the development of SEGS-III to SEGS-IX projects. The projects were driven by the availability of state and federal investment tax credits and solar property tax exclusion [21,78]. Table 6 summarizes the main characteristics of the 9 SEGS plants.

In SEGS-I, the HTF supplied thermal energy to a heat storage system (with a total capacity of nearly 3 h of full-load turbine operation). The stored heat produced steam, which was further heated by a natural-gas-fired super heater before entering the turbine. The main purpose of the SEGS-I storage system was to permit electricity generation variations to coincide with peak periods when sales are most profitable. This storage system was damaged by fire in 1999 and was not replaced. The second stage, SEGS-II uses a different approach to supply electricity in peak or special periods. A natural gas boiler is arranged in parallel with the solar field, configuration retained in the other Luz plants. Steam is generated and superheated by the solar heat. The auxiliary heater is used at peak periods when the field is unable to produce enough steam to drive the turbine at full load, that is, during low and non-solar hours. PURPA regulations, however, restrict natural gas to 25% of the total effective annual thermal plant energy input [24,26]. PURPA initially limited the plants to 30 $MW_e$, but this limit was later raised to 80 $MW_e$ (SEGS-VIII and SEGS-IX) [21].

In 1991, Luz declared bankruptcy while in the process of building the SEGS-X and planning three more plants, as a result of delays in the extension of the California solar property tax exemption, the inability to find financing and falling energy prices. However, the SEGS plant ownership was not affected by the Luz situation, because the plants had been developed as independent power projects, and were owned by investor groups (typically composed of large corporations, insurance firms, utility investment divisions and some individual participants) and in fact, at present still continue routine operation. Luz was acquired by Solel Belgium in 1992 [21,23,78].

A 6-year project to reduce operation and maintenance (O&M) costs at plants employing CSP technology was initiated by Sandia National Laboratories and Kramer Junction Operating Company in 1993. O&M technologies developed during the course of the program were demonstrated at the 5 Kramer Junction plants. Improvements were made in solar energy collection efficiency, O&M information management, reliability of solar field low loop hardware, plant operating strategy, and cost reduction associated with environmental issues. A 37% reduction in annual O&M costs was achieved [80].

### 3.1.2. SSPS project

The technology was also considerably stimulated in Europe when the first SEGS plants were erected. The Small Solar Power System Project/Distributed Collector System (SSPS/DCS) was the most representative project (see Fig. 6). The project goal was to design and build an experimental CSP plant. It was sponsored by the International Energy Agency (IEA) with the co-operation of 9



**Fig. 6.** SSPS/DCS plant at the PSA.

countries (Austria, Belgium, Germany, Greece, Italy, Spain, Sweden, Switzerland and the United States), was designed and built by the Acurex Corp. (California, United States), M.A.N. (Munich, Germany) and *Técnicas Reunidas S. A.* (Madrid, Spain), and was operated by the *Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt* (DFVLR[1]). The project was begun in 1977 [81,82].

The 0.5-$MW_e$ DCS plant was comprised of three solar fields an American single-axis-tracking system manufactured by the Acurex Corp. (model Acurex 3001, see Table 1 and Fig. 1) and two German two-axis-tracking systems manufactured by M.A.N. (model Helioman 3/32, see Table 2 and Fig. 2). After heating in the solar fields, HTF (Santotherm 55 thermal oil) was pumped to the top of a storage tank, and from the tank to a steam generator to produce steam for a steam turbine (Fig. 6). Low-temperature oil was returned from the steam generator to the bottom of the tank, where it was pumped back to the solar fields [11,82,83].

The Acurex collector field, with a land use factor of 0.27, was east–west oriented, had a total aperture area of 2674 $m^2$, and was made of 10 two-row collector loops. The west M.A.N. field (M.A.N.-West), with a land use factor of 0.32, had a total aperture area of 2688 $m^2$ and was made of 14 collector loops. A third 10-loop 2244-$m^2$ field (M.A.N.-East) was erected in March 1984. The main advantages of the M.A.N.-East field were a minimized field pipe-length layout, especially on the hot side, improved insulation and elimination of the long field pipe support (fins). The field control was also improved and the new field showed more stable operating characteristics than the previous field [11,83].

The 5-$MWh_t$ single thermocline storage tank was a vertical cylindrical shell about 15 m high and 4.2 m in diameter, and had a working volume of 115 $m^3$. A second storage system was also installed. It was a dual-medium storage tank, i.e., thermal energy was stored by means of thermal oil and cast-iron slabs. This tank consisted mainly of a vertical-steel vessel, which contained a stack of 115 cast-iron slabs [11,83].

A steam generator and a steam turbine/generator unit were the major power conversion subsystems. The steam generator consisted of a separate economizer, evaporator with a steam/water separation drum mounted above, and super heater. The steam turbine was an eight-stage condensing turbine with one extraction for the deaerator manufactured by Stal-Laval. The turbine drove the air-cooled electric generator by means of a single-reduction parallel-shaft gear. The electric generator output was 577 $kW_e$ with a 0.8 power factor. The calculated overall efficiency of the turbine/generator unit was 22.7% [11,83].

This experimental plant was in operation at the PSA (Almería, Spain) between 1981 and 1985. The following conclusions were arrived at [83]:

- More energy was available for collection with a two-axis tracking collector than a single-axis collector (energy supply). However, the SSPS single-axis collector was able to make better use of the energy available to it than the two-axis systems.
- The thermal efficiency in the original M.A.N. field (M.A.N.-West) was approximately 21%, and around 30% in the new M.A.N. field (M.A.N.-East).
- Thermal to electrical conversion efficiencies were much lower than expected.
- The two-axis collector systems were difficult to maintain and required more maintenance than the single-axis collector system.

### 3.1.3. Current state of CSP in the United States

The American Western Governors' Association (WGA) Clean and Diversified Energy Advisory Committee had established energy Task Forces on Advanced Coal, Biomass, Energy Efficiency, Geothermal, Solar, Transmission and Wind with roadmapping guidelines for implementation of 30,000 $MW_e$ of new clean diversified energy generation by 2015, a 20% increase in energy efficiency by 2020 and build-up of adequate transmission capacity for the region over the next 25 years. In its 2006 report to the WGA, the Solar Task Force identified 4 $GW_e$ of high-quality CSP sites in the South Western US [75]. A number of these states have special policy requirements stimulating renewable energy development, provided for the in their Renewable Portfolio Standard (RPS). A RPS is a state policy that requires electricity providers to achieve a minimum percentage of their power from renewable energies by a certain date. Table 7 shows the states with such RPS [84]. Two of the states in Table 7 already have commercial CPS plants (see Table 8).

The Saguaro Station organic Rankine turbine can be operated automatically [85]. It was built under a federal production tax credit available for utility ownership [79]. NSO is a solar-only system with 30 min of thermal storage, used to minimize the effects of transients, and a very small natural gas heater, mostly used for freeze protection, because only a 2% supplement is allowed in Nevada [87]. It was built under a special power purchase agreement with a 30% federal investment tax credit [79].

There are also two plant projects under development. The first one, the Solana Generating Station, will be the largest solar power plant in the world. It will be built and operated by Abengoa Solar (Spain), which has recently signed a contract with APS. The plant will be located on agricultural land 100 km southwest of Phoenix, near Gila Bend (Arizona), and the electricity generated will be sold to APS for 30 years. It will have a 280-$MW_e$ gross electricity capacity, with $2 \times 140$-$MW_e$ conventional steam turbines and around 250 $MW_e$ net capacity, with a 220 ha aperture area on 800 ha of land. The plant will have a 6-h molten-salt thermal storage system. It is expected to go on grid in 2011 [55,88,89].

The second plant will be located in Ivanpah (California) and will be built and operated by BrightSource (whose subsidiary is Luz II) as the consequence of a series of contracts between Pacific Gas and Electricity Company (PG&E) and BrightSource for a total of 500 $MW_e$ of power to be supplied from solar thermal power. It will have a 100-$MW_e$ capacity and produce 246 $GW_eh$/year [90].

### 3.1.4. Current state of CSP in Europe

The most important European policy documents, in which targets and global strategies are specified, are the European Union White Paper for a Community Strategy and Action Plan; Energy for the Future: Renewable Sources of Energy, European Union Directive 2001/77 on the Promotion of Electricity Produced from Renewable Energy Sources in the Internal Market, and the European Union policies for security of energy supply and for the implementation of the Kyoto Protocol [91]. By 2010, the share of renewable energy sources should represent 12% of the gross

**Table 7**
Renewable Portfolio Standard in the United States.

| State | Amount | Year | State | Amount | Year |
|---|---|---|---|---|---|
| Arizona | 15% | 2025 | Nevada | 20% | 2015 |
| California | 20% | 2010 | New Hampshire | 16% | 2025 |
| Colorado | 20% | 2020 | New Jersey | 22.5% | 2021 |
| Connecticut | 23% | 2020 | New Mexico | 20% | 2020 |
| Delaware | 20% | 2019 | New York | 24% | 2013 |
| Hawaii | 20% | 2020 | North Carolina | 12.5% | 2021 |
| Illinois | 25% | 2025 | Oregon | 25% | 2025 |
| Massachusetts | 4% | 2009 | Pennsylvania | 18% | 2020 |
| Maryland | 9.5% | 2022 | Rhode Island | 15% | 2020 |
| Maine | 10% | 2017 | Texas | 5880 MW | 2012 |
| Minnesota | 25% | 2025 | Washington | 15% | 2020 |
| Montana | 15% | 2015 | Wisconsin | 10% | 2015 |

[1] Nowadays the DLR.

**Table 8**
Main characteristics of current CSP plants in operation in the United States.

| Plant | Saguaro Solar Generating Station | Nevada Solar One, NSO |
|---|---|---|
| Location | Red Rock, near Tucson (Arizona) | Boulder City, Nevada |
| Average solar resource (kWh/$m^2$ year) | 2000 | 2500 |
| Developer | Acciona Solar Power[a] and ORMAT | Acciona Solar Power and Siemens |
| First year of construction | 2004 | 2006 |
| Operator | Arizona Public Service (APS) | Solargenix Energy |
| Power utility | APS | Nevada Power Company |
| First year of operation | 2006 | 2007 |
| Net output capacity ($MW_e$) | 1 | 64 |
| Net electricity production ($GW_eh$/year) | 2 | 134 |
| Land area (ha) | 4.69 | 162 |
| Solar field aperture area (ha) | 1.034 | 35.720 |
| Collectors | SGX1 (Acciona Solar Power) | SGX2 (Acciona Solar Power) |
| Reflectors manufacturer | Flabeg | Flabeg |
| Absorber tubes manufacturer | SCHOTT (PTR 70) | 62% SCHOTT (PTR 70) + 38% Solel (UVAC) |
| Solar field outlet temperature (°C) | 290 | 390 |
| Heat transfer fluid | Xceltherm 600 | VP1 |
| Turbine manufacturer | ORMAT (Israel) | Siemens (Sweden) |
| Power fluid | Pentane | Steam |
| Power fluid pressure (MPa) | 2.23 | 8.61 |
| Power fluid temp. (°C) | 204 | 371 |
| Power cycle | Recuperated ORC | RR |
| Global average annual efficiency (%) | 12 | 20 |
| References | [43,79,85] | [43,44,79,86] |

[a] Acciona Energy (Spain) purchased 55% of Solargenix Energy and formed Acciona Solar Power in 2006.

energy consumption [92] and 22.1% of the electricity generation mix [93].

*3.1.4.1. Spain.* Spain, with a DNI of 2000 kWh/$m^2$ year, is one of the international leaders in the implementation of CSP technology for electricity generation [73]. Spanish legislation adopted European goals in the Renewable Energies Plan, approved in 1999 (PFER) and revised in 2005 (PER). The 1999 Plan set a goal of 200 $MW_e$ of CSP plant installed capacity by the end of 2010. This was increased to 500 $MW_e$ in the 2005 Plan. European Union Directive 2001/77 was also adopted by the 2005 PER, setting the share of renewable energy sources at 29.4% of the electricity generation mix in Spain [94–96].

Spanish Law 54/1997 on the electricity sector, approved in 1997 [97], lays out the general lines for liberalizing this sector. This Law provides for a "Special Regime" for self-producers or facilities with installed capacity of 50 $MW_e$ or less based on co-generation, non-consumable renewable energies, biomass or any type of biofuel or non-renewable waste. This Law not only introduced competition in the Spanish electricity sector, but also made this principle compatible with the achievement of other purposes, such as improving energy efficiency, reducing consumption and protecting the environment.

Royal Decree 2818/1998 [98] followed this precedent by establishing a special legal framework for electricity production for Special Regime facilities based on an 18.0-c€/$kWh_e$ premium over the market price. Although all solar facilities were included in the special regime, only solar photovoltaic facilities received a premium and no CSP project prospered. In Royal Decree 841/2002 [99], the two types of solar facilities were considered separately and an incentive premium of 12 c€/$kWh_e$ for solar thermal plants between 100 $kW_e$ and 50 $MW_e$ capacity was introduced, subject to revision every 4 years. This incentive was still not bankable and the amount did not cover the cost or risks involved for first CSP projects to become feasible.

The solar thermal premium was therefore increased in Royal Decree 436/2004 [100], which improved the solar thermal feed-in premium and made CSP projects bankable and attractive for investors. This Royal Decree included the following features [96]:

- Power producers had two options for sale. They could either transfer it to the power distribution company, with the electricity sale price stated as a single regulated tariff (tariff model), or sell on the free market at the going market price plus a premium (premium model). Representative data are shown in Table 9.
- Maximum plant power capacity of 50 $MW_e$. Higher capacities must sell on the market.
- 12% (tariff model) or 15% (premium model) natural gas or propane back-up to maintain the temperature of the storage tank.
- Annual adaptation to the *Tarifa Media de Referencia*, TMR (average reference tariff) subject to 4-year revision.
- Incentive revision after implementation of the first 200 MWe capacity.

Spanish Royal Decree 661/2007, approved in 2007 [101], differentiated from the former in the following [75,102]:

- The incentives were increased (see Table 9).
- Auxiliary fuel can be used to maintain the HTF temperature to compensate for the lack of solar radiation. No auxiliary fuel is specified.
- Annual revision to the Retail Price Index.
- Conditions will be reviewed by 2010 or when 500 $MW_e$ have been installed.

**Table 9**
Special regime incentives under the RD 436/2004 and the RD 661/2007.

| | RD 436/2004 | | RD 661/2007 | |
|---|---|---|---|---|
| | Reference premium | Regulated tariff | Reference premium | Regulated tariff |
| First 25 years | 260% TMR (21.01 c€/$kWh_e$)[a] | 300% TMR (24.24 c€/$kWh_e$)[a] | 25.40 c€/$MWh_e$ | 26.94 c€/$kWh_e$ |
| Rest of the life | 210% TMR (16.97 c€/$kWh_e$)[a] | 240% TMR (19.39 c€/$kWh_e$)[a] | 20.32 c€/$MWh_e$ | 21.55 c€/$kWh_e$ |

[a] Assuming TMR = 80.8 €/MWh.

As a result, there is more than 10 $GW_e$ CSP capacity planned in Spain, with 2 PTC plants in operation (Andasol-I and Ibersol Puertollano), 13 plants under construction (see Table 10) and more than 200 planning projects [73,103].

Andasol-I received a € 5-million grant form the 5th Framework Programme of the European Union and finance from the European Investment Bank [75]. Both Andasol-I and Andasol-II have an integrated 1010-$MWh_t$ molten-salt thermal storage system to extend plant full-load operation 7.5 h beyond daylight hours. The storage system consists of two tanks (29,000 tons of molten salts) with 385 °C charge temperature and 295 °C discharge temperature [104,109]. In addition, the Andasol plants also include two 15-$MW_{th}$ auxiliary gas heater to heat the thermal oil when solar radiation is insufficient and to keep salt from solidifying.

Moreover, ACS-Cobra is constructing another three 50-$MW_e$ plants similar to the Andasol projects, Extresol 1 (in collaboration with Sener) and Extresol 2 in Torre de Miguel Sesmero (Badajoz), and Manchasol 1 in Alcázar de San Juan (Toledo). This company is also planning 2 more plants, Extresol 3 in Badajoz, and Manchasol 2 in Ciudad Real. Solar Millenium, in collaboration with M.A.N. Ferrostal, has recently started the construction of Andasol-III next to the previous Andasol projects [73,103].

The Ibersol Puertollano plant (no thermal storage) has a fossil-fuel auxiliary system, for periods of low solar radiation, plant shutdowns and transitories [106]. Iberdrola is planning 11 other plants in Spain with characteristics similar to Puertollano plant [73].

Solnova plants (no thermal storage) have a natural-gas fired HTF heater in parallel with the solar field [107,108]. Abengoa Solar is also planning another 6 plants similar to Solnova-I in Spain, Solnova-II and Solnova-V in Sanlúcar la Mayor (Seville), Helios 1 and Helios 2 in Ciudad Real, and Ecija 1 and Ecija 2 in Ecija (Seville) [73].

In addition to the 9 plants mentioned above, there are 5 more 50-$MW_e$ plants currently under construction, La Risca in Alvarado (Badajoz) and Palma del Río-I in Palma del Río (Córdoba) by Acciona, Lebrija I in Lebrija (Seville) by Solel/Sacyr, La Florida in Alvarado (Badajoz) and La Dehesa in La Garrovilla (Badajoz) by SAMCA [73,103]. Other companies are also planning and promoting 50-$MW_e$ plants in Spain, Albiasa Solar in Saucedilla (Cáceres), Acciona in Majadas de Tietar (Cáceres) and Palma del Río (Córdoba), ARIES in Alcázar de San Juan (Ciudad Real) (Aste 1 and Aste 2 plants) and Badajoz (Axtesol plant), and Torresol (60% Sener and 40% Masdar) in Seville (Termesol plant) and Cadiz (Arcosol plant) [50,73].

*3.1.4.2. Italy.* Italy (DNI about 2000 kWh/$m^2$ year) has initiated the promotion of CSP to increase the renewable energy share of total electricity generation. In May 2008, Italian Decree 11/4/2008 was passed [110], establishing the criteria and ways to promote solar power production in thermodynamic cycles. The significant points are:

- Incentives for electricity from solar thermal or hybrid solar power plants without any limitations on the solar share. The incentive tariffs to be added to the selling price are proportional to the solar share: 28 c€/$kWh_e$ for a solar share of up to 0.15, 25 c€/$kWh_e$ for a solar share between 0.15 and 0.50, and 22 c€/$kWh_e$ for a higher solar share.
- Incentives remain the same for 25 years, without any adjustment for inflation, and can be added to the grid sale price.
- Incentives are valid for plants in operation before 31 December 2012. The incentive tariffs will be reduced 2% each calendar year for plants that start up operation between 1 January 2013 and 31 December 2014. After that date, incentive tariffs will be set taking the cost of conventional fuels and solar components into consideration.
- If the solar component is integrated with another renewable energy source (for example biomass), the hybrid plant receives a Green Certificate for electricity produced with renewable energy sources under the Green Certificate Mechanism (today in the range of 18–22 c€/$kWh_e$).
- The national target set by the decree is a total installed collector aperture area of 2 million square meters.
- All solar power plants, hybrid plants included, must be equipped with a thermal storage system with unitary storage capacity of no less than 1.5 $kWh_{th}$ per square meter aperture.
- The minimal plant collector aperture is 2500 $m^2$, however, there is no upper limit on plant size.

**Table 10**
Main characteristics of CSP plants constructed or under construction in Spain.§: Unavailable datum.

| Plants | Andasol-I and Andasol-II | Ibersol Puertollano | Solnova-I, Solnova-III & Solnova-IV |
|---|---|---|---|
| Location | Marquesado de Zenete (Granada) | Puertollano (Ciudad Real) | San Lúcar la Mayor (Seville) |
| Average solar resource (kWh/$m^2$ year) | 2150 | 2071 | 1940 |
| Owner | ACS-Cobra (75%) & Solar Milennium S.A. (25%) | Iberdrola Energía Solar[a] | Abengoa Solar |
| Developer | ACS-Cobra and Sener | Iberdrola Energía Solar | Abengoa Solar |
| First year of construction | 2006 (Andasol-I) 2007 (Andasol-II) | 2007 | 2007 (Solnova-I) 2008 (Solnova-III and IV) |
| Operator | ACS-Cobra and Sener | Iberdrola Energía Solar | Abengoa Solar |
| Power utility | Sevillana Endesa | Iberdrola | Sevillana Endesa |
| First year of operation | 2008 (Andasol-I) 2009 (Andasol-II, expected) | 2009 | 2009 (expected) |
| Net output capacity ($MW_e$) | 49.9 | 50 | 50 |
| Net electricity production (GWh/year) | 179 | 120 | 114.6 |
| Land area (ha) | 200 | 135 | 120 |
| Solar field aperture area (ha) | 51.012 | 29.000 | 29.430 |
| Collectors | 624 SKAL-ET150/AS1 | 352 ET150 | 360 ET150 |
| Reflectors manufacturer | Flabeg | Flabeg | Rioglass |
| Absorber tubes manufacturer | SCHOTT | Solel | SCHOTT |
| Solar field outlet temperature (°C) | 400 | 390 | 393 |
| Heat transfer fluid | Thermal oil (Dow thermal A) | Thermal oil | Thermal oil |
| Turbine manufacturer | Siemens | Siemens | Siemens |
| Power fluid | Steam | Steam | Steam |
| Power fluid pressure (MPa) | 10 | 10 | 10 |
| Power fluid temp. (°C) | 377 | 380 | 380 |
| Power cycle | RS/RRg/RR | RS/RRg/RR | RS/RR |
| Global annual efficiency (%) | 16 | [a] | 19 |
| References | [41,104,105] | [106] | [107,108] |

[a] 90% Iberdrola Renovables, 10% Instituto para la Diversificación y el Ahorro Energético (IDAE).

In 2000, the Italian Government allocated €55 million to ENEA for CSP development and a national demonstration programme. The project, called Archimedes, consists of the development of the first Italian PTC solar plant integrated in an existing 370-$MW_e$ CC plant in Priolo Gargallo (Sicily), where DNI is 1725 kWh/$m^2$ year. The Italian utility, ENEL, became involved in the project in 2004 [75,87]. The plant will consist of a 5-$MW_e$ solar field with molten salt as the HTF, two storage tanks operating at different temperatures (290 and 550 °C), and a superheated steam generator [51,73].

*3.1.4.3. Greece.* In 2006, Greece passed Law 3468/2006, containing a feed-in tariff for solar thermal electricity generation [111], which transposed European Union Directive 2001/77/EC. It also seeks to promote electricity generation from renewable energy sources and high efficiency cogeneration of electricity and heat plants in the internal electricity market. This Law grants 25 c€/$kWh_e$ for CSP plants with less than 5 $MW_e$ capacity and 23 c€/$kWh_e$ for over 5 $MW_e$ on the mainland. On unconnected islands, this tariff is 2 c€/$kWh_e$ higher [111].

Theseus is a 52-$MW_e$ CSP plant with PTC that is under development on the island of Crete (Greece). Solar Millennium owns 75% of the project and Flabeg, Fitchner and OADYK own the remaining 25%. A local project company, THESEUS S.A., has been founded. The solar field will be 30 ha [112].

*3.1.4.4. Portugal.* In 2007, the Portuguese Ministry of the Economy and Innovation passed Decree Law 225.2007, which revised the feed-in tariffs set Decree Law No. 33 A/2005 to 29.3 c€/$kWh_e$ for CSP plants under 10 $MW_e$ and 15–20 c€/$kWh_e$ for CSP plants over 10 $MW_e$ [113].

### *3.1.5. Current state of CSP in the North of Africa*

North Africa offers a huge potential for electricity production from CSP due to its high solar irradiance. The opportunity for exporting CSP electricity to Europe is one of the major drivers for CSP growth in the region. This is opening up new opportunities for economic and technical cooperation between the two regions and will help Europe in its long-term $CO_2$-emissions reduction target.

*3.1.5.1. Algeria.* Algeria has the highest solar potential in the Mediterranean Basin. Coastal areas in Algeria receive an annual solar irradiance of 1700 kWh/$m^2$ year while the highlands and Sahara receive 1900 kWh/$m^2$ year and 2650 kWh/$m^2$ year respectively. It has been estimated that 82% of the total land is available for installing CSP plants [73].

Algeria has now taken on its own domestic commitment, with the aim of increasing the solar percentage in its energy mix to 5% by 2010. But beyond this, Algeria is seeking a close partnership with the European Union in which Algerian plants would contribute to the power Europe needs to meet its green energy target. To realize these plans, and to enhance the participation of the private sector, New Energy Algeria (NEAL) was created in 2002 [114]. It has also set up a national programme that would encourage power production from renewable energy resources through its Sustainable Energy Development Plan by 2020 [73]. Decree 04-92, published in the Official Journal of Algeria in March 2004, promotes renewable energy systems, including CSP for hybrid solar-gas steam cycles, as well as integrated solar and gas-CC plants. This decree sets a premium for the total ISCCS electricity production, depending on the solar share, from a 100% premium for a 5–20% solar share up to a 200% premium for a solar share over 25% [115].

In June 2005, NEAL published the first Request for Proposals (RfP) for a 150 $MW_e$ ISCC plant with PTC to be partly financed and operated privately. The Abengoa Group was awarded the contract and reached financial closure with NEAL in 2007. Both the German investment bank *Kreditanstals fur Wiederaufbau* (KfW) and the European Investment Bank are financing the project [71,75,116]. Main characteristics of this plant are summarized in Table 11.

*3.1.5.2. Morocco.* Morocco, which receives about 2000 kWh/$m^2$ year DNI in around 30% of its territory [73], also offers great potential for CSP. It is Morocco's goal to increase the share of renewable energies from 0.24% in 2003 to 10% in 2011 and close to 20% in 2020 [116].

In 1999, the Global Environment Facility (GEF) awarded the Morocco national electric utility (*Office National de l'Electricité*, ONE) a grant of US$ 50 million to cover the incremental cost of an ISCC project. Additional financing has already been committed by the African Development Bank as a soft loan. In 2007, an agreement was signed by Abengoa and ONE, giving the Spanish company the go-ahead to build the 470 $MW_e$ station at Beni Mathar [75,108,116,117]. The main characteristics of this plant are summarized in Table 11.

*3.1.5.3. Egypt.* Egypt has set up a New and Renewable Energy Authority (NREA, a dependency of the Ministry of Energy) that is responsible for promoting renewable energy resources [73]. Its

**Table 11**
Main characteristics of CSP plants built or under construction in North Africa. §: Unavailable datum.

| Location | Hassi R'Mel (Algeria) | Ain Beni Mathar, north of Oujda (Morocco) | Kuraymat, south of Cairo (Egypt) |
|---|---|---|---|
| Average solar resource (kWh/$m^2$ year) | 2500 | 2290 | 2431 |
| Owner/Developer | SPP1[a] | ONE | NREA |
| Constructor | SPP1 | Abengoa Solar | Iberdrola/Mitsui (CC) and Orascum/Flagsol (solar) |
| First year of construction | 2007 | 2008 | 2008 |
| Operator | SPP1 (25 years) | Abengoa Solar (5 years) | [b] (2 years) |
| Power utility | Sonatrach | ONE | EEA |
| First year of operation | 2009 (expected) | 2009 (expected) | 2010 (expected) |
| Overall output capacity ($MW_e$) | 150 | 470 | 140 |
| Net solar output capacity ($MW_{th}$/$MW_e$) | 95/25 | [b]/20 | 61/20 |
| Net total electricity production (GWh/year) | [b] | [b] | 852 (33.4 solar) |
| Solar field aperture area (ha) | 18.00 | 18.70 | 13.08 |
| Collectors | 216 SKAL-ET | SKAL-ET | SKAL-ET |
| Solar field outlet temperature (°C) | 393 | 393 | 393 |
| Steam turbine capacity ($MW_e$) | 70 | [b] | 76 |
| Power cycle | ISCC | ISCC | ISCC |
| Gas turbine capacity ($MW_e$) | 80 | [b] | 73 |
| References | [87,108] | [75,108,117] | [40,87,120] |

[a] Solar Power Plant 1, Abengoa (66%) and NEAL (34%) joint venture.
[b] Unavailable datum.

renewable energy strategy currently targets a 3% share of the Egyptian electricity demand, mainly from solar, wind and biomass applications, by 2010, with additional contributions from other renewable energy applications [116].

In 1995, the NREA and the Egyptian Electricity Authority (EEA) funded a technological feasibility study for an ISCCS in Egypt, where more than 95% of the territory receives over 2000 kWh/m$^2$ year DNI, and about 80% of the land is available for use. Three solar technologies were considered mature for large-scale application, the PTC, the air receiver power tower and the molten-salt receiver power tower. The study concluded that the ISCCS with PTCs or air tower are equally attractive [118]. This was followed by a SolarPACES START mission in 1996. The Ministry of Electricity and Energy (MOEE) entrusted a joint NREA, MOEE and EEA committee with the evaluation of the potential for integrating CSP technologies into the Egyptian electricity network. The committee concluded that the ISCCS with PTC is the most economical near-term approach for beginning implementation of solar thermal power in Egypt [119].

A project to build an ISSC plant with PTC has been underway since then. The project received a US$ 50 million grant from the GEF to cover the incremental cost of the solar power plant. The NREA contracted two consortia to build the CC and the solar field in September 2007 (see Table 11) [40,75,116,120].

*3.1.6. Current state of CSP in the Middle East*

Middle East countries are developing solar power capabilities as a consequence of estimated power shortages from large-scale construction, and rising concern about the longevity of fossil fuels. Almost all Middle East territory is exposed to high solar irradiance levels (around 2400 kWh/m$^2$ year in Israel, Jordan and Saudi Arabia). Potential for export is also being explored by these countries with the European Union [73].

*3.1.6.1. Israel.* The Israeli Ministry of National Infrastructure, which is responsible for the energy sector, decided in 2002 to make CSP a strategic share of the Israeli power market, with a minimal power unit of 100 MW$_e$, and the option of increasing the CSP contribution up to 500 MW$_e$ by 2010, and 1000 MW$_e$ by 2020. Israel has also committed an increased share in alternative and renewable energies to at least 15–20% by 2020. In September 2006, new feed-in incentives for solar-driven independent power projects (IPP) valid for 20 years were announced. The tariff is approximately 16.3 US$cents/kWh, for plants with installed capacity over 20 MW$_e$. For smaller plants, from 100 kW$_e$ to 20 MW$_e$ range, the tariff is 20.4 US$cents/kWh. The regulations further stipulate that a fossil fuel back-up of less than 30% of total capacity is allowed [121].

There are plans to build a new solar station in The Negev desert, which covers 55% of Israel's land, every year for the next 20 years [71,73,87,121]. The first 150-MW$_e$ CSP plant with PTC will be probably built by Solel Solar Systems at Ashalim, in the Negev desert. The plant will use 70% solar energy and 30% natural gas. The project is managed by Israel Electric Company and the final owner will be an IPP [19,116].

*3.1.6.2. Iran.* Iran has been promoting a CSP plant since 1994, when a Joint German-Iranian Expert Group on Solar Thermal Power, sponsored by the German Federal Ministry of Environment and the Iranian Power Development Company (IPDC), did a concept study for a 100-MW$_e$ CSP plant. In 1996 IPDC contacted the GEF for funding the incremental cost of the solar field, however, the GEF was not in a position to allocate the additional resources needed. A feasibility study on ISCC with PTC was done by the NIROO Research Institute, FLABEG Solar and Fichtner Solar. Yazd was chosen as the most preferred site with 2511 kWh/m$^2$ year DNI. Due to the lack of GEF funding, Iran changed the plant configuration in 2005, and now intends to build a 20-MW$_e$ (67 MW$_{th}$) solar field in a 300-MW$_e$ natural-gas-fired CC plant [116,122,123].

*3.1.6.3. UAE.* The UAE offers excellent solar resources for CSP, receiving an average DNI of around 2200 kWh/m$^2$ year. The fact that CSP requires vast areas of land and that land is scarce and expensive in this country, could make it difficult for CSP to be a cost-effective option for producing electricity. According to a UAE government document, renewable energy could contribute 6–7% of the peak demand by 2020 [73]. A 100-MW$_e$ PTC plant, called Shams 1, is being planned by Masdar in Abu Dhabi [124].

*3.1.7. Current state of CSP in other countries*

*3.1.7.1. India.* The Rajasthan Renewable Energy Corporation (RREC) published an RfP in June 2002 for a 140 MW$_e$ ISCCS, integrating a PTC field of about 22 ha to supply a solar share of 30 MW$_e$. Solar radiation in the region selected (Mathania, Rajasthan, near Jodhpur) is around 2240 kWh/m$^2$ year DNI. The incremental solar costs were to be covered by a GEF grant for US$49 million with further financing by a soft loan from the German Investment Bank (KfW), and loans from India and the state of Rajasthan. Limited competition, high risks on uncertain fossil fuel supply and some government disputes delayed the project. After extensive review of the underlying technical and project implementation concept, GEF is now requesting that all Indian participants reaffirm their commitment to continue the project [71,87,116].

*3.1.7.2. Mexico.* Mexico's *Comisión Federal de Electricidad* (CFE) issued an RfP in 2002 for a 250-MW$_e$ gas-fired CC plant with an optional integrated 25 MW$_e$ PTC field. The incremental solar costs should be covered by a GEF grant. As investor response to this concept was very limited, in 2003 it was decided that an Engineering Procurement and Construction (EPC) scheme with CFE and GEF grants should be pursued, and the solar field would no longer be an option but compulsory. At first, the plant location was Cerro Prieto, near Mexicali in Baja California Norte (DNI about 2600 kWh/m$^2$ year), but in 2005 the site for the CC plant, called Agua Prieta II, was moved to Sonora, and it was suggested by the CFE that its size be doubled from 250 to 500 MW$_e$ [71,116]. The final ISCC will have a 480 MW$_e$ capacity and the solar field capacity will be 31 MW$_e$ (peak).

*3.1.7.3. Brazil.* Brazil has extensive, semi-arid regions receiving a DNI on the order of 2200 kWh/m$^2$ year. The highest potential radiation is in the São Francisco River Basin and the Sobradinho area in the Northeast. Potential sites in Brazil are close to the equator with the consequential optical advantage. Immense land areas are available for solar thermal applications. Januária and Itacarambi have excellent topographic conditions, grid access, cooling water, road access, low wind speeds, and moderate ambient temperatures with little daily variation. These sites receive annual direct solar radiation from 1800 to 2300 kWh/m$^2$ and can easily accommodate large-scale solar power plants [87].

In 1997, a SolarPACES START Mission went to Brazil. According to this report, Luz and Flagsol initiated SEGS-project development activities in Brazil in 1989 and for this purpose formed a consortium with *ABB do Brazil* and the *Tenenge/Odebrecht* group. The consortium performed site surveys and pre-feasibility studies, but no project came out of it. Both off-grid village and irrigation loads and grid-connected power for cities are promising markets for the deployment of CSP in Brazil [125].

**Table 12**
DSG research projects in the 90s in Europe [28].

| Project | Financiation | Duration | Partners | Goals | References |
|---|---|---|---|---|---|
| HIPRESS[a] | Deutsches Gobierno federal and Baden-Wutemburg gobierno regional | 1992–1994 | ZSW | Experimental study of heat transfer coefficients and two-phases flow configurations | [131] |
| GUDE[b] | Deutsches Ministerium für Forschung und Entwicklung | 1992–1995 | SIEMENS KWU, DLR, ZSW, Technische Universität München | Integration of a DSG solar field in a combined-cycle plant | [132,133] |
| PRODISS | Deutsches Ministerium für Forschung und Entwicklung | 1995 | SIEMENS KWU, DLR | Continuation of GUDE; analysis of transients | [134] |
| ARDISS[c] | European Commission; II JOULE Program | 1994–1997 | CIEMAT, CONPHOEBUS, INETI | Design, construction and testing of an absorber tube for DSG | [135,136] |
| STEM[d] | European Commission; APAS Program | 1995–1996 | CIEMAT, Unión Fenosa, Iberdrola, Universidad de Las Palmas, ULP, UMIST, Falgsol, ZSW, Intecsa, Solel, DLR, Siemens | Viability study of PTC plants in the Mediterranean and DSG plants | [137,138] |

[a] High pressure experiments.
[b] Grundlegende Untersuchungen zur Solares Direktverdampfung von Wasser nach dem Einspritzprinzip.
[c] Advanced Receiver for Direct Solar Steam.
[d] Solar Thermal Electricity for Mediterranean Countries.

*3.1.8. DSG technology*

The HTF selected in all the above-mentioned commercial solar power plants is thermal oil. Direct Steam Generation (DSG) in the absorber tubes is another possibility of economic and energetic interest for such plants, because of the following advantages over HFT technology [28]:

- Environmental risks associated with thermal oil are eliminated (fires and leaks).
- The maximum temperature of the cycle can be increased over the current limit of around 400 °C imposed by thermal oils which degrade at higher temperatures.
- Overall plant efficiency is higher because the oil/steam heat exchanger is unnecessary. This makes the solar field requirement and investment lower.
- Plant configuration is simplified because both heat exchanger and auxiliary thermal oil systems are eliminated.
- Operation and maintenance costs are reduced because there must be an auxiliary heating system for thermal oil, and 3% must be replaced annually.

All the above advantages decrease the cost of the power produced by about 15%. The disadvantages of this technology are the following [28]:

- Its higher operating pressure requires suitable hydraulic components, which increases costs.
- Water may freeze.
- The water flow must always be faster than the minimum required to avoid stratificated flow in the evaporation zone.
- Control systems required are more complex and expensive, due to the two-phase flow inside absorber tubes and the different thermodynamic properties of water and steam.

Although the first PTC already used DSG technology (see Section 2.1), and research in this area started in the 80s, at the same time as the commercial use of the HTF technology, during the last three decades commercial projects have not decided for it due to the potential problems and uncertainties associated with the two-phase water/steam flow in the absorber tubes.

*3.1.8.1. Theoretical studies.* The Solar Energy Research Institute (SERI, United States) compared HTF, DSG and flashing technologies [126], and studied DSG process stability [127]. The encouraging results of these studies and the work done at Tel Aviv University (Israel) on water/steam two-phase stability in tilted tubes [128,129], were a major boost for Luz International Ltd, which in 1988 started an ambitious research programme called Advanced Trough System (ATS). The project was organized in four phases, with the goal of testing the theoretical results and demonstrating the technology's feasibility. Although most of the phases were successful, it was not completed because of the demise of Luz in 1991 [28]. So as not to lose the knowledge gained, Mr. E. Dagan made a review of DSG technology in 1992 for the PSA [130].

*3.1.8.2. First test set-ups.* Since that time, several European companies and research centres have undertaken a number of projects studying the main technical uncertainties associated with this technology. Table 12 summarizes these projects.

The National University of Mexico Engineering Institute (*Universidad Nacional de México*, UNAM) also did research on this technology in the 90s. Several tests were done in four east-west-oriented, 14.5-m-long PTCs, with a 2.5-m aperture width and 0.625-m focal length. These tests demonstrated process technical feasibility and the usefulness of multiwall tubes for generating electricity on a small-scale [139,140].

*3.1.8.3. DISS project.* Although the above-mentioned research projects managed an enormous advance in the study of DSG technology, they were performed in the laboratory or under real conditions on a small-scale. Therefore, the next necessary step forward was real-scale analysis and technology feasibility demonstration. This landmark was reached in two European projects, Direct Solar Steam (DISS) and Integration of DSG Technology for Electricity Production (INDITEP), successfully carried out at the PSA (see Fig. 7).



**Fig. 7.** DISS test loop at the PSA.

The two-phase DISS project was funded by the European Commission within the framework of the E.U. JOULE Program (contracts No. JOR3-CT95-0058 and JOR3-CT98-0277). The DISS-Phase I Partnership was composed of research centres (CIEMAT, DLR and ZSW), electric utilities (IBERDROLA, ENDESA, UNIÓN ELÉCTRICA FENOSA) and industry (INABENSA, PILKSOLAR and SIEMENS-KWU). During this phase (1996–1998), a life-size test facility was designed and implemented at the PSA to investigate the feasibility of the DSG process in PTCs under real solar conditions [141].

The DISS facility consists of two subsystems, the solar field and the Balance of Plant (BOP). The solar field was made up of a single north-south-oriented, 550-m-long row of 11 modified LS-3 PTCs connected in series, and around 3000 $m^2$ of reflecting mirrors. The collector row is divided into a water prehating and evaporating section and a steam superheating section by a water/steam separator. The solar loop thermal power is 2 $MW_{th}$. In the BOP, the superheated steam produced by the solar field is condensed in an air-cooled condenser and converted into feed water that is pumped back to the solar field inlet and water injection system in a closed loop [28,141,142].

The Phase II Partnership was also composed of research centres (CIEMAT, DLR and ZSW), electric utilities (Iberdrola and Endesa), engineering companies (INITEC) and industry (INABENSA and FLABEG Solar). The main purpose of DISS Phase II (1998–2001) was experimental research on the three basic DSG processes (once-through, injection and recirculation) to find out which was the best for a commercial DSG CSP plant. They tested two-phase flow stability, different start-up and shutdown procedures, several control schemes for the three DSG processes, the influence of the inclination of the absorber pipes on the two-phase flow parameters, the temperature profile in the absorber pipe cross sections and the optical and thermal performance of the DISS collectors. After operating the test facility for more than 5500 h, the most important conclusion is the certainty that DSG is technically feasible in PTCs with horizontal absorber tubes [28,141–146].

*3.1.8.4. INDITEP project.* The valuable experience and know-how acquired in the DISS project was later applied in the INDITEP project. The main aim of this project was the design of the first precommercial DSG solar power plant, where the thermal energy delivered by a 5-$MW_e$ DSG solar field was used to feed an RS cycle. This project was promoted by a Spanish-German Consortium of engineering companies, power equipment manufacturers, research centres and businesses involved in the energy market: *Iberdrola Ingeniería y Consultoría*, CIEMAT, DLR, FLAGSOL Solar GmbH, FRAMATONE, *GAMESA Energía y Servicios S.A.*, *INITEC Tecnología S.A.*, *Instalaciones Inabensa S.A.* and ZSW. The European Commission also funded the project under Contract ENK5-CT-2001-00540 [147,148].

The solar field designed was composed of seven parallel rows of ET-100 collectors, with 10 collectors in every row, 3 for water preheating, 5 for water evaporation, and 2 for steam superheating. The recirculation mode was selected as the operating mode. In addition, some main components of the solar field, such as are water/steam separators and control schemes, were also investigated [147,148,149].

The next logical step in this research area is the design, construction and operation of a demonstration DSG plant. Two projects are being developed for this purpose, with the participation of some of the DISS and INDITEP partners, Puertollano GDV and REAL-DISS.

*3.1.8.5. Puertollano GDV pre-commercial plant.* This project consists of the construction of a 3-$MW_e$ pre-commercial DSG solar power plant in Puertollano (Ciudad Real, Spain), although in the beginning it was planned to be built at the PSA. The project is being developed under a co-operation agreement that was signed by five Spanish entities in 2006, and was modified in December 2007, so the current members of the Consortium are the CIEMAT, Iberdrola (electric utility), *Instituto para la Diversificación y el Ahorro Energético* (IDAE) and SENER (an engineering firm) [150].

The solar field is composed of four parallel rows of 10 ET-100 collectors connected in series, with the INDITEP Project configuration. The solar field will operate in recirculation mode with a water injector in the steam superheating section to control the outlet steam temperature. It is designed to deliver superheated steam at 411 °C/7 MPa at nominal inlet conditions of 120 °C/7.5 MPa. The turbine is an AFA-46 two-stage non-reheating superheated steam turbine, manufactured by AG Kuenhle, Kopp & Kausch, which works at a nominal 400 °C/6.5 MPa. The power block has a dry, not a wet cooling system, because the high water consumption associated with Rankine power cycles significantly reduces the feasibility of CSP plants in arid areas with high insolation and lacking in water resources. In addition, the plant will also be provided with a gas-fired auxiliary heater [150]. Construction of this plant will start by the end of 2009.

*3.1.8.6. REAL-DISS project.* The German-Spanish REAL-DISS project aims not only at the development of a DSG demonstration plant, but also all eventual commercial components required. The project partners are the DLR and seven companies, ENDESA, Flagsol GmbH, MAN Ferrostal, Senior-Berghöfer, SCHOTT Solarthermie GmbH, Ed. Züblin AG and Milenio Solar [151].

As in this case, the maximum operating conditions in the solar field are up to 500 °C and 10 MPa, additional components must be developed. The project is divided into three detailed design, erection and operation phases, first of a test set-up, then of a 5-$MW_e$ demonstration plant, and finally, the 50-$MW_e$ commercial plant [151].

During Phase I, which started in 2007, and is scheduled to end in 2009, a number of suitable key components for such operating temperatures will be developed and tested: absorber tubes (SCHOTT), flexible tube connections (Senior-Berghöfer) and storage system (Ed. Züblin and DLR). In addition, a test set-up will be erected at the ENDESA 1.1-$GW_e$ coal power plant in Carboneras (Almería, Spain) for testing the new components under real operating conditions [151,152].

*3.1.8.7. Solarlite commercial plants.* A demonstration plant using DSG technology with Solarlite collectors has recently been built in Woltow (Germany) (see Section 2.3.3). This co-generation power plant uses the solar steam to produce electricity with a 40-$kW_e$ turbine and also heat to maintain the optimum water temperature (about 26 °C) in the fish tank at a fish farm. The solar field has a 400-$m^2$ aperture area, operating conditions are 64–215 °C/1.65 MPa and nominal power is 220 $kW_{th}$. It also has a straw steam boiler [52,153].

Two other co-generation power plants with DSG and Solarlite collectors are planned, in Soneva Fushi (Maldive Islands) and Soneva Kiri (Thailand). The Soneva Fushi project will have a 7200-$m^2$ aperture area and 4.6 $MW_{th}$/0.55 $MW_e$ peak capacity, and the Soneva Kiri project will have an 11880-$m^2$ aperture area and 4.6 $MW_{th}$/1.1 $MW_e$ peak capacity. Both will operate at 330 °C/30 bar and will also supply heat for solar cooling and/or sea water desalination [52].

It is also planned to install this collector in two DSG solar power plants in Kanchanburi and Suphanburi (Thailand). They will have a 90160 $m^2$-aperture area, with 35.8 $MW_{th}$/10 $MW_e$ peak capacity and 62-$MWh_{th}$ energy storage, and will operate at 330 °C/30 bar [52].

### 3.2. Industrial process heat (IHP)

According to the latest IEA statistics (for 2006), industry is one of the major consumers of energy worldwide-around 30% [70]. In 2007, there were about 90 operating IPH solar thermal plants[2] with a total capacity of about 25 $MW_{th}$ (35,000 $m^2$) worldwide. The key sectors are food and beverages including wine, textile, transport equipment, metal and plastic treatment, and chemicals. And the most suitale processes are cleaning, drying, evaporation and distillation, blanching, pasteurisation, sterilisation, cooking, melting, painting, and surface treatment [154].

Of the total energy used by industry, a major portion, approx. 45–65%, is used for direct application of industrial process heat in the preparation and treatment of goods. The thermal energy demand for IPH is below 300 °C, and 37.2% of the total IPH demand is in the range of 92–204 °C [155]. According to the ECOHEATCOOL study done in 32 countries,[3] 27% of the thermal energy demand for IPH is between 100–400 °C [156]. For that reason, one of the most important applications of a small-sized PTC is IPH.

The interest in using solar systems for supplying the thermal energy required by industry is not only because so much of such energy is consumed in this sector, but also because loads are usually constant throughout the year, and the plants usually already have maintenance crews who could also care for the solar fields, thus ensuring operation of the system at peak efficiency [9,157]. The drawbacks of using solar energy in IPH are [9,157]:

- Land availability and cost. Existing rooftops often not large or strong enough to support the solar field.
- Industrial effluents. An industrial environment involves higher risk of corrosion of solar collectors than a commercial or residential setting.
- Non-constant energy source.
- Availability of conservation alternatives. Many plants can employ simple, inexpensive energy conservation techniques which should precede any commitment to solar energy. These include using waste heat from high-temperature processes to supply low-temperature processes (such as boiler feed-water preheat).
- Economics. Industry often requires payback periods of less than 5 years.

Three alternative design concepts exist for generating the solar steam required by IPH [158]:

- *Unfired boiler or heat exchanger* (*HE*). This has a heat transport loop, which delivers hot fluid from the collectors to an unfired boiler or heat exchanger and recirculates the fluid to the collectors through a circulating pump. In this boiler the hot fluid furnishes the heat required to convert feed water into saturated or superheated steam at the required pressure and temperature. The working fluid commonly used in this indirect concept is thermal oil.
- *Flash boiler* (*FB*). This is another indirect process in which the water from the flash boiler is pressurized and circulated through the solar field and heated to a temperature between 180 and 200 °C. The water is pressurized and maintained at the required pressure by a circulating pump to prevent boiling within the collectors or the field piping. When the heated water from the collector field enters the boiler flash chamber, due to the change in pressure in the vessel, a part of it is converted into steam, which is delivered to the steam mains of the industrial process. The rest of the water is recirculated through the collector field. Make-up water is fed from the storage tank. Flashing is up to about 4–6%, depending on the temperature of the heated water.
- *DSG*. This is a direct system, in which the water is partially or completely boiled in the collector. In the first case, water is circulated through a steam drum where steam is separated from the water. Feed water is added to the steam drum or mixed with the recirculated water at a rate regulated by a level controller in the drum. In the second type, feed water is added directly to the collector field inlet.

In 1976, the US DOE began funding a number of solar IPH field tests, through the Solar Industrial Process Heat Program, most of them with PTCs. In 1978, the SERI began providing technical support for this programme during design reviews and specifying data acquisition and monthly performance requirements [157]. Table 13 summarizes the most outstanding PTC IHP facilities in the United States, some of which are still in operation. Some other facilities of this type in other countries are summarized in Table 14.

### 3.3. Domestic hot water and space heating

One of the most widespread applications of solar thermal energy is hot water production. According to an IEA report for 2006, solar thermal collector capacity in operation worldwide was about 127.8 $GW_{th}$ (182.5 millions $m^2$), most of it domestic, both for DHW (kitchen, shower, laundry and sanitation facilities) and space heating [171].

Israel is the country with the oldest solar legislation, in force since 1980. The law's success has made it largely superfluous. Today, more than 90% of Israel's solar thermal market is voluntary, retrofitted in existing buildings or systems larger than required by law [172]. Currently, a number of countries are promoting solar water heating systems. A clear example is Spain, where current legislation included in the building code requires that all new or remodelled DHW installations and covered swimming-pool heating have to have a solar system to supply a certain amount of the energy demanded [173]. Another example is Portugal, where the new Portuguese building code includes a requirement for solar thermal installations, which must be a minimum of 1 $m^2$ per person, or some other form of renewable energy providing a similar energy saving, however this requirement only covers certain types of buildings [174].

The temperatures at which energy is required by these applications are below 100 °C. Therefore, conventional solar collectors with suitable efficiencies (FPC, CPC or evacuated tube collectors) could be employed. However, when a large amount of hot water is demanded, a large collection area, which sometimes becomes excessive, must be installed. In this case, PTCs might be of interest, because they supply thermal energy at higher temperatures than those required by the load and, therefore, higher demands can be covered by mixing the hot solar fluid with another cooler.

Examples of applications with high hot water consumption rates are large swimming-pool heating systems, and DHW and space heating for large buildings, such as industrial buildings, factories, hospitals, educational centres, sport facilities, government buildings, prisons, airports, bus and train stations, etc. In most situations, a minimum hot water consumption of about 1900 l/day would be needed to make a PTC system, which is more effective for large, 7-day-a-week hot water users, to be feasible [167].

The advantages of PTCs over the solar collectors traditionally used in water heating facilities are their lower thermal losses and, therefore, higher efficiency at the higher working temperatures reached, smaller collecting surface for a given power requirement, and no risk of reaching dangerous stagnation temperatures, since

[2] China and Japan not included.
[3] EU25 + Bulgaria, Romania, Turkey, Croatia, Iceland, Norway and Switzerland.

**Table 13**
IHP facilities with PTCs in the United States.

| Location | Company or institution | Year | Solar collector | Aperture area ($m^2$) | Fluid/steam generation concept | Application | Process temperature (C) | References |
|---|---|---|---|---|---|---|---|---|
| Sacramento (California) | Campbel Soup Co. | 1977 | Acurex | 681 | Water/HE | Can washing | 88 | [9] |
| Pasadena (California) | Home Cleaning & Laundry Co. | 1978 | Jacobs Del Co. | 604 | Pressur. water/FB | Steam for laundry | 182 | [9,82,159] |
| Fairfax (Alabama) | West Point Pepperell Inc. | 1978 | Honeywell Inc. | 773 | Pressur. water/FB | Fabric drying | 160 | [9,160,161] |
| San Antonio (Texas) | Lone Star Brewering Co. | 1979 | Solar Kinetics T-700 | 876 | Oil Therminol 55/HE | Steam production | 178 | [9,82,162] |
| Haverhill (Ohio) | U.S.S. Chemicals Co. | 1979 | Solar Kinetics 700 | 4682 | Oil Therminol 60/HE | Industrial chemicals production | 189 | [9,82,163] |
| Peppeko (Hawaii) | Hilo Coast Processing Co. | 1980 | Solar Kinetics | 4672 | [a] | Sugar-cane processing | 204 | [9,164] |
| Sherman (Texas) | Johnson & Johnson | 1980 | Acurex | 1068 | Pressur. water/FB | Steam production | 174 | [9,165] |
| Newberry Springs (California) | NL Industries Inc. | 1981 | Jacobs Del Co. | 949 | [a] | Hectorite drying | 189 | [9,166] |
| Hobbs (New Mexico) | Famariss Refinery; Southern Union Co. | 1981 | Solar Kinetics | 937 | Oil/HE | Crude oil processing | 191 | [9,163] |
| Shenandoah (Georgia) | Bleyle of America Inc. | 1982 | General Electric | 4578 | [a] | Steam production and DHW | 399 | [9] |
| Ontario (Oregon) | Ore-Ida Foods Co. | 1982 | Suntec | 883 | Pressur. water/FB | Steam production | 214 | [9,82] |
| Dalton (Georgia) | Dow Chemical Co. | 1982 | Suntec | 923 | Thermal oil/HE | Latex manufacturing | 186 | [9,82] |
| Chandler (Arizona) | Gould Electronics | 1982 | Solar Kinetics | 5620 | Thermal oil/HE | Copper foil production | 95 | [167,168] |
| San Leandro (California) | Caterpillar Tractor Co. | 1982 | Solar Kinetics 360 | 4682 | Pressur. water/HE | Washing of tractors parts | 113 | [9,82] |
| Winter Haven (Florida) | U.S. Citrus and Subtropical Products Laboratory | 1983 | Prototype | 9.9 | Drying products directly on the focus | Mango slices drying | [a] | [169] |
| Modesto (California) | Frito-Lay Inc. | 2008 | IST-PT1 | 5065 | Pressure Water/HE | Oil heating to fry potato and corn chips | 249 | [170] |
| Tuba City (Long Island) | DOE | 2009 | IST-PT1 | 160 | Press. Water/HE | Distillation of contaminated water | [a] | [170] |

[a] Unavailable datum.

in that case, a control system sends the collectors into off-focus position. The disadvantages of PTCs are that its solar-tracking system increases installation and maintenance costs, and the need to clean their components also increases maintenance costs. As PTCs can only use beam solar radiation, their installation is geographically limited, and at very high wind speeds operation must be interrupted and the collectors sent into off-focus position.

There are numerous facilities in the United States where a PTC solar field is employed for supplying hot water. Indeed, the DOE created the Federal Energy Management Program (FEMP) for financing Federal facility energy conservation and renewable energies projects, mainly in prisons. Several facilities were built under this program, most of them with IST collectors [167]. Table 15 shows the main characteristics of some of these facilities.

Studies with operating data from some of these facilities conclude that the average overall efficiency of the solar field is about 40%, while the peak overall efficiency is around 60%. The simple pay-back period is 8 years, and the expected service life is 30 years [175].

### 3.4. Air-conditioning and refrigeration

The energy demand associated with air-conditioning in most industrialized countries has been increasing noticeably in recent years, causing peaks in electricity consumption during hot weather and disturbing the transport and distribution grid. The main reasons for this growing energy demand are the increased thermal loads, improved living standards and occupant comfort demands,

**Table 14**
IHP facilities with PTCs in the rest of the world.

| Location | Company or institution | Year | Solar collector | Aperture area ($m^2$) | Collector outlet temperature (°C) | Fluid/steam generation concept | Application | Process temperature (°C) | References |
|---|---|---|---|---|---|---|---|---|---|
| Alcorcon (Madrid, Spain) | Lactaria Castellana | 1981–1987 | Casa Auxini | 600 | 180–220 | Thermal oil | Steam production for sterilisation | [a] | [168] |
| Merida (Badajoz, Spain) | CARCESA | 1982–1988 | [a] | 1024 | 180 | Thermal Oil Heliotermo 2550 | Sterilization of meat products | 207 | [168] |
| Aguas de Moura (Portugal) | UCAL | 1985 | [a] | 1280 | 140–280 | Thermal oil | Dairy | 188 | [168] |
| Pisticci (Italy) | PISTICCI | [a] | Two-axis | 1728 | 280 | Steam | Chemical | [a] | [168] |
| Targa- ssonne, (France) | TARGASSONNE | [a] | [a] | 770 | 280 | Thermal oil | Thermal | [a] | [168] |
| Mysore (India) | Government Silo Factory | 1989 | One-axis | 192 | 179 | Pressur. Water/FB | Steam production for silk printing | 150 | [155] |
| El Nasr (El Cairo, Egypt) | New and Renewable Energy Authority | 2004 | IST-PT1 | 1900 | [a] | Pressur. Water/FB | Steam production for pharmaceutical chemicals | 173 | [87,153]; |

[a] Unavailable datum.

**Table 15**
Examples of PTC facilities connected to high-consumption water-heating systems in the United States.

| Location | Company or institution | Year | Solar collector | Aperture area ($m^2$) | Fluid | Application | Process temperature (°C) | Storage capacity ($m^3$) | References |
|---|---|---|---|---|---|---|---|---|---|
| Yuma (Arizona) | U.S. Army Yuma Proving Ground | 1979 | Solar Kinetics | 1191 | Water | DHW, AC and space heating | [a] | [a] | [175] |
| Brighton (Colorado) | Adams County Detention Facility | 1987 | IST-PT1 | 555 | Water + ethylene glycol | DHW | 85 | 19 | [167] |
| Tehachapi (California) | California Correctional Institution | 1991 | IST-PT1 | 2677 | Water + ethylene glycol | DHW and space heating | 104–116 | None | [176,177] |
| Golden (Colorado) | Jefferson County Detention Facility | 1996 | IST-PT1 | 633 | Water | DHW | [a] | 17 | [170,175] |
| Phoenix (Arizona) | Phoenix Federal Correctional Institution | 1999 | IST-PT1 | 1584 | Water + propylen glycol | DHW | 55 | 87 | [167,178] |
| San Antonio (Texas) | U.S. Army Fort Sam Houston | 2003 | IST-RMT | 420 | Water | DHW, AC and space heating | 88 | None | [58,175] |

[a] Unavailable datum.

and architectural characteristics and trends, such as an increasing ratio of transparent to opaque areas in the building envelope [179]. The above, along with refrigeration requirements in the food processing industry and conservation of pharmaceutical products in developing countries, are leading to a renewed interest in air-conditioning and refrigeration systems powered by renewable energies, especially solar thermal, which works efficiently, and in certain cases, approaches competitiveness with conventional cooling systems.

Solar thermal systems, in addition to the typical advantages of renewable resources (environmentally-friendly, naturally replenished, distributed), are very suitable for air-conditioning and refrigeration demands, because solar radiation availability and cooling requirements usually coincide seasonally and geographically. Solar air-conditioning and refrigeration facilities can also be easily combined with space heating and hot-water applications and with solar passive techniques, increasing the yearly solar fraction of buildings.

In spite of the tremendous research effort made in theoretical analysis and experimental projects since the 70s, and the enormous interest related to solar air-conditioning and refrigeration systems, their commercial implementation is still at a very early stage, due mainly to the high costs associated with these systems and the clear market supremacy of conventional compression chillers. Other obstacles to their large-scale application are the shortage of small heat pump equipment and the lack of practical experience and acquaintance among architects, builders and planners with their design, control and operation [180].

In the last few years, many research and demonstration activities have started up in several countries. A study carried out in the framework of the IEA Solar Heating and Cooling (SHC) program, within the activities of Task 25, "Solar-Assisted Air-Conditioning of Buildings", (that ended in 2004 and was followed in 2006 by Task 38 "Solar Air-Conditioning and Refrigeration"), found that there were about 70 air-conditioning facilities with solar collectors in Europe [179,181]. Another study under the Solar Air Conditioning in Europe (SACE) project, financed by the European Commission, in which five countries participated, found about 54 solar air-conditioning facilities [179,180].

The Coefficient of Performance (COP) is higher for a LiBr–$H_2O$ double-effect than for a single-effect absorption chiller, but it requires thermal energy at temperatures of 140–160 °C [179], at which performance of conventional collectors is not good enough. As PTCs are highly efficient at these temperatures, the combination of these two systems is of great interest [182]. Connection of $NH_3$–$H_2O$ absorption chillers to a solar system requires solar collectors able to work efficiently at temperatures above 95 °C [179], such as the PTCs or high-efficiency stationary collectors. Air-conditioning and refrigeration facilities driven by a PTC solar field are still infrequent. However, several test facilities using this technology have appeared in the literature during the last 50 years as summarized in Table 16.

### 3.5. Pumping irrigation water

To make use of PTCs for pumping irrigation water, the thermal energy produced by the solar field must be converted into mechanical energy for driving the water pump. This application is of especial interest in isolated zones and rural areas, where the grid is far away and fuel transport is economically restrictive. Furthermore, this application has two main advantages: solar energy is abundant in most arid regions, where agriculture depends on irrigation, and it is an operation where the intermittency of solar radiation is usually acceptable, without the necessity of an intermediate storage system.

In this respect, Bahadori [191] compared different direct conversion systems (photovoltaic, thermoelectric and thermoionic) and thermodynamic power production cycles (Rankine, Brayton and Stirling). In the Rankine-cycle he analyzed several solar collectors (solar ponds, FPC and PTC), types of expanders (turbines, reciprocating engines and rotary displacement), working fluids, and operating temperatures. The author emphasized that the operation and maintenance of the solar pumps should be very simple because they are generally located in areas with no skilled manpower and access is very difficult for delivery of any special equipment or parts.

Although pumping irrigation water is not the most frequent application of PTCs, there are several examples of this kind of facility. In fact, the first commercial PTC plant was used to pump water for irrigation (see Section 2.1). In addition to this reference, there are other commercial and experimental examples in the literature.

On an experimental level, a 1-kW water pump was installed and assessed at the UNAM in 1976. The pump was driven by a 12-$m^2$ PTC field with DSG in the absorber tube. Unfortunately, solar system global efficiency was found to be only 2%. This poor result led to a new project, without satisfactory improvement [192].

A feasibility study conducted by the University of Arizona (United States) in 1975–1976 found that lower cost, improved solar devices, improved energy use management and availability of modestly priced capital were the key engineering and economic factors preventing successful marketing and use of solar-powered

**Table 16**
Some PTC facilities connected to solar cooling systems (absorption chillers).

| Location | Company or institution | Year | Solar collector | Aperture area ($m^2$) | Collector outlet temperature (°C) | Fluid | Application | Process temperature (°C) | Chiller type/model/fluid pairs/power (kW) | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Montlouis (Pyrénées-Orientales, France) | *Laboratoire de l'Energie Solaire* | 1957 | Prototype | 1.5 | [a] | $NH_3$ | Ice production (6 kg/day) | 90 | SE[b]/prototype/$H_2O$-$NH_3$/[a] | [183] |
| Florida (USA) | University of Florida | 1957 | Prototype | 4.46 | 288 | Cotton-seed oil | AC[c] | [a] | SE/prototype/$H_2O$-$NH_3$/[a] | [184] |
| Sulaibiya (Kuwait) | Kuwait Institute for Scientific Research | 1984 | Prototype | 63.2 | [a] | Water | AC | 98.9 | SE/ARKLA Solaire 501/ BrLi–$H_2O$/10.55 | [185] |
| Juzbado (Salamanca, Spain) | *Empresa Nacional de Uranio* (ENUSA) | 1985 | [a] | 1080 | 180 | Oil Heliotermo 2550 | Cold generation | [a] | SE/[a] | [168] |
| Kharagpur (India) | Solar Energy Laboratory, Indian Institute of Technology | 1989 | Prototype | 1.5 | [a] | Water | Food Preservation (3 °C) | 92 | SE/Himalux/[a]/0.25/ | [186] |
| Amman (Jordan) | University of Jordan | 1991 | Prototype | 3.6 FPC +0.15 PTC | [a] | Water | AC | 95 | SE/prototype/BrLi-$H_2O$/[a] | [187] |
| Madrid (Spain) | Polytechnic University of Madrid | 2000 | [a] | [a] | 150 | Thermal oil | Refrigeration in isolated areas | [a] | SE/prototype/$H_2O$-$NH_3$/2 | [188] |
| Dalaman (Turkey) | Iberotel Sarigerme Park | 2004 | Solitem PTC-1800 | 360 | 180 | Pressur. water | Steam for AC and Laundry | 144 | DE[d]/Broad/BrLi-$H_2O$/116 | [60,189] |
| Gebze (Turkey) | Gebze Institute of Technology | 2006 | Solitem PTC-1800 | 360 | 180 | Pressur. water | AC and hot water supply | 144 | DE/Broad/BrLi-$H_2O$/260 | [153,190] |
| Douglas (Arizona, USA) | Chochise College Campus | 2006 | IST-PT1 | 634 | [a] | Pressur. water | AC and space heating | 121 | SE/Energy Concepts/ $H_2O$-$NH_3$/210 | [170] |
| Long Island (New York, USA) | Steinway and Sons | 2009 | IST-PT1 | 533 | 200 | Pressur. water | AC, space heating and steam production | [a] | DE/Broad/BrLi-$H_2O$/315 | [170] |

[a] Unavailable datum.
[b] Single-effect.
[c] Air-conditioning.
[d] Double-effect.

**Table 17**
Pumping irrigation water commercial plants with PTCs.

| Location | Company or institution | Year | Solar collector/ efficiency (%) | Aperture area ($m^2$) | Fluid | Rankine cycle efficiency (%)/ fluid/power (kW) | Process temperature (°C) | Irrigated field area (ha)/flow ($m^3$/min)/ depth (m) | Storage capacity ($m^3$) | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Phoenix (Arizona, USA) | Gila River Ranch | 1977 | PTC/44-50 | 564 | Water | [a]/R113/$37_{mechanic}$ | 149 | [a]/38/3 | None | [2,193] |
| Willard (New Mexico, USA) | Paragon Resources | 1977–1978 | Acurex + Solar Kinetics/25 | 625 + 651 | Oil Caloria HT-43 | 15/R113/$19_{mechanic}$ | 216 | 49/2.6/32 | 26 | [2,82,194] |
| Coolidge (Arizona, USA) | Dalton Cole Farm | 1979 | Acurex 3001/38.6 | 2140 | Oil Caloria HT-43 | 20/Toluene/$200_{electric}$ | 288 | 80/[a]/100 | 189 | [82,193] |

[a] Unavailable datum.

**Table 18**
Examples of solar desalination plants with PTCs.

| Location | Company or institution | Year | Solar collector | Aperture area ($m^2$) | Collector outlet temperature (°C) | Fluid | Desalination technology | Production capacity ($m^3$/day) | Storage System | References |
|---|---|---|---|---|---|---|---|---|---|---|
| La Paz (Baja California Sur, Mexico) | Government of Mexican Republic & Federal Republic of Germany | 1979 | Dornier Systems FPC + MAN PTC | 518 (FPC), 160 (PTC) | 105 (FPC), 125 (PTC) | Water | MSF (10 stages) | 10 | 24 h | [211,212] |
| Kuwait | Kuwait Institute for Scientific Research & Swiss Federal Institute of Technology | 1984 | PTC | 220 | [a] | Water | MSF (12 stages) | 100 | 7 $m^3$ | [212,213] |
| Arabian Gulf | General Atomic Design | [a] | PTC | 53960 | 288 | [a] | MED | 6000 | [a] | [212] |
| PSA (Almeria, Spain) | CIEMAT and DLR | 1987 | Acurex 3001 | 2672 | 300 | Thermal oil Santotherm 55 | MED (14 stages) | 72 | 115 $m^3$ | [214,215] |
| Al-Wagan (Al-Ain, United Arab Emirates) | [a] | [a] | PTC | 675 | [a] | Thermal Oil | MED (55 stages) + MSF (75 stages) | 500 | 5000 kg | [216] |

[a] Unavailable datum.

**Table 19**
Examples of heterogeneous ($TiO_2$) and homogeneous (Photo-Fenton, PF) photocatalysis in PTCs.

| Location | Company or institution | Year | Solar collector | Aperture area ($m^2$) | Type of photocatalysis | Application | Results and conclusions | References |
|---|---|---|---|---|---|---|---|---|
| Sutherland (Australia) | CSIRO | 1985 | PTC-1[a] | 0.25 | $TiO_2$ | Degradation of chlorobenzene, benzoic acid and 4-chlorophenol | Complete detox. and also some disinfection | [217] |
| USA | Sandia and SERI | 1990 | PTC-1 | 465 | $TiO_2$ | Degradation of salicylic acid (low concentration)/ trichloroethylene and trichloroethane | Better results with $H_2O_2$/higher degr. rate as higher radiation | [218,219] |
| Almeria (Spain) | PSA | 1993 | PTC-2[b] Helioman | 384 | $TiO_2$ | Degradation of pentachlorophenol (pesticide and word preservation) | Easy degr. and enhanced results with $H_2SO_4$ | [220,221] |
| Almeria (Spain) | PSA | 1996 | PTC-2 Helioman | 384 | $TiO_2$ | Degradation of atrazine (herbicide) | Efficient detox. and better results with $H_2SO_4$ | [222] |
| Cologne (Germany) | DLR | 1997 | PTC-2 Helioman | 32 | $TiO_2$ | Degradation of $NH_3$/$NH_4^+$ | Similar results to laboratory results | [223,224] |
| Madrid (Spain) | CIEMAT | 1997 | PTC-1 | 3 | PF | Removal of lindane (pesticide) | Reduction of 99% in acceptable times | [225] |
| Almeria (Spain) | PSA | 1999 | PTC-2 Helioman and CPC | 8 (PTC) | $TiO_2$ | Study of photoelectrochemical reactors ($TiO_2$ deposited) | Several advantages detected | [226,227] |
| Mexico | UNAM | 2000 | PTC-1 | 1.82 | $TiO_2$ | Degradation of sodium benzene sulfonate (toothpaste, shampoo, etc.) | 94% degradation without $H_2O_2$; 100% with $H_2O_2$ | [228] |
| Almeria (Spain) | PSA | 2001 | PTC-2 Helioman and CPC | 32 (PTC) 9.24 (CPC) | $TiO_2$ | Degradation of isoproturon (herbicide) using supported $TiO_2$ and fixed bacteria | Degr. rates in CPC 5 times more efficient than in PTC | [229] |
| Morelos (Mexico) | UNAM | 2002 | PTC-1 and tubular FPC | 1.82 (PTC) | $TiO_2$ | Degradation of Aldrin (pesticide) | Better with $H_2O_2$; similar degradation on both coll. | [230] |
| Barcelona (Spain) | Barcelona University | 2002 | PTC-1 | 0.087 | PF | Treatment of nitrobenzene (pesticide and explosive) | 95% mineralization | [231] |
| Morelos (Mexico) | UNAM | 2004 | PTC-1; TC;[c] CPC and VC[d] | 0.72 (each one) | $TiO_2$ | Degradation of oxalic acid (intermediate of the degradation of aromatic compounds) | Similar degradation on all coll. CPC the best overall performance | [232] |
| Japan | AIST[e] | 2004 | PTC-2 | 1 | $TiO_2$ | Degradation of toluene and acetaldehyde (VOC) | Degr. of 79% toluene and 93% acetaldehyde | [233] |
| Barcelona (Spain) | Barcelona University | 2004 | PTC-1 and CPC | 0.174 (PTC) 5.93 (CPC) | PF | Mineralization of phenol (pollutant in industrial effluents) | Similar intrinsic kinetic constants in both coll. | [234] |

[a] One-axis PTC.
[b] Two-axis PTC.
[c] Tubular Collector.
[d] V-Trough Collector.
[e] National Institute of Advanced Industrial Science and Technology.

pumping plants. Four solar power plants were constructed to evaluate different technologies for supplying pumping energy. Plants erection and operation were funded by the DOE and directed by Sandia National Laboratories. One of them used photovoltaic cells to provide up to 25 kW of electricity for irrigation pumping and other on-site applications at the University of Nebraska farm near Meade (United States). PTC and Rankine cycle were the main components of the other three systems [193]. Table 17 summarizes the main features of these 3 plants, where the first 2 plants were directly connected to pumps and the third one was a solar thermal-electric power plant, sized to drive pumps providing the required irrigation water.

Two facilities in Ghana, designed by the *Steven Foundation* in the United States around 1987, must also be mentioned. Both facilities used a PTC field to generate steam. In one case, a small steam engine drove a deep-well pump, whereas in the other, steam injection was used in a liquid-piston pump for surface water. Wood-fired boilers were incorporated because the DNI was often insufficient to operate the plant in the tropical climate [195].

### 3.6. Desalination

The problem of an adequate potable water supply may well become one of the most serious challenges facing the world in this century. Solar desalination is one of the most promising technologies for confronting this problem because water shortage and solar energy availability frequently coincide geographically. Solar energy can be used for water desalination either directly, producing the distillates inside the solar collector, or indirectly, connecting the solar system to a conventional desalination plant. Moreover, the indirect concept can be achieved with either a thermal or a photovoltaic solar system. Whereas solar photovoltaic systems are used in electric desalination plants, solar thermal systems can be connected to both a thermal and an electric desalination plant (by thermal to electric intermediate conversion).

The PTC's suitability for solar desalination has been studied in several different types of desalination, such as Reverse Osmosis (RO) [196–201], Multi-Effect Distillation (MED) [202–210] and Multi-Stage Flash (MSF) [205,208,210]. A few commercial or pilot plants were implemented. These MSF or MED plants, built in the 80s, are summarized in Table 18.

### 3.7. Solar chemistry

The widespread presence of hazardous organic chemical compounds, mainly in water but also in air, has motivated interest in finding alternative environmentally friendly solutions for the treatment and/or removal of these compounds. Over the last two decades, the near ultraviolet component of the solar spectrum has been utilized for degrading these organic compounds with $TiO_2$ (heterogeneous photocatalysis) or Fe(II)/Fe (III) ions combined with $H_2O_2$ (homogeneous photocatalysis or photo-Fenton). These processes have been demonstrated to be successful and show huge potential for their commercial application.

Concentrated solar energy augments the detoxification process, because more high-energy photons are projected directly into the stream of water or air. Consequently, there are several examples of solar detoxification using a solar concentrating system. When the solar concentrating system selected is a PTC, a transparent tube (usually glass) is placed in the focal line of the reflector instead of the metal absorber tube, as photo-reactor. Some examples of photocatalytic devices using PTCs are summarized in Table 19.

In conclusion, according to several authors [235,236], reaction rates in heterogeneous photocatalysis with $TiO_2$ depend on the number of photons achieved by the catalyst, as can be seen in Fig. 8.

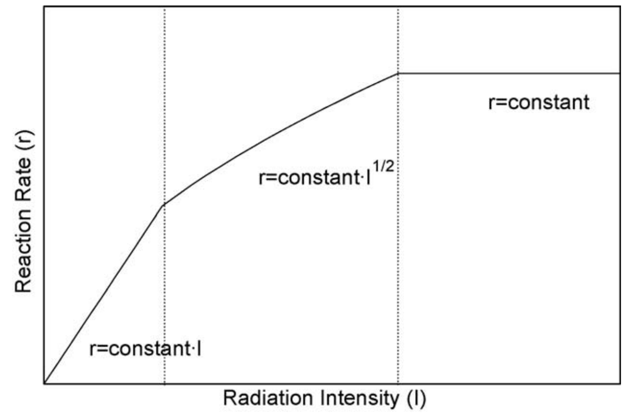



**Fig. 8.** Photocatalysis reaction rate versus irradiance [238].

Behaviour is linear when solar irradiance is low, proportional to the square of the solar irradiance when the solar irradiance is intermediate and constant when the solar irradiance is very high. Accordingly, in $TiO_2$ photocatalysis, there is a point at which the reaction rate becomes independent of radiation intensity. This has caused research to gradually focus on CPC systems instead of PTCs for solar photocatalysis applications with $TiO_2$ [237]. Other reasons that PTCs are not currently used for either type of photocatalysis are economic, as they require a solar tracker, and cannot be used on cloudy days.

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